SuperKEKB Beam Instrumentation (BI) challenges & experience

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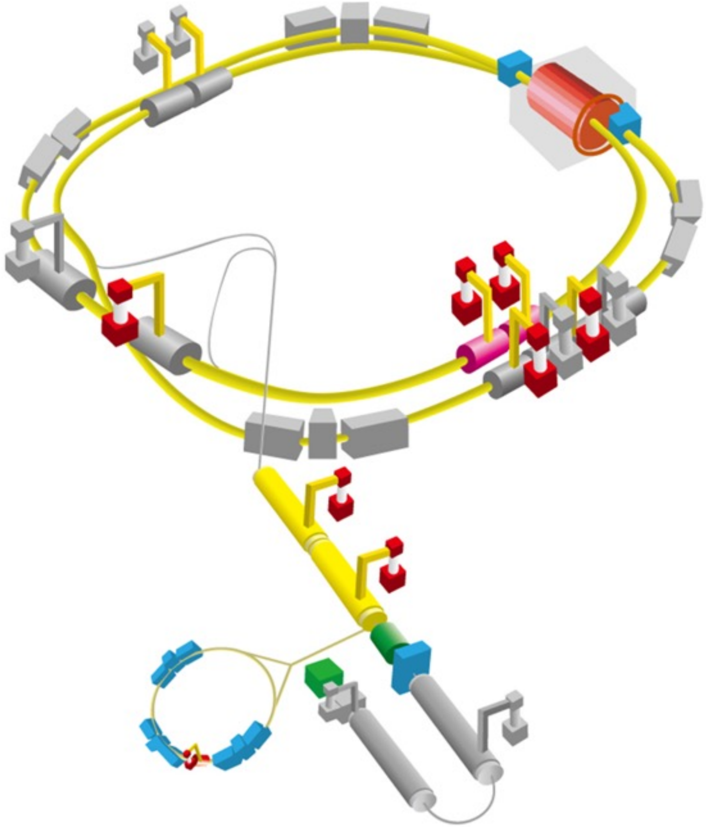
2022/9/14 eeFACT

Contents

SuperKEKB

- SuperKEKB
  - collider with 7 GeV electron and 4 GeV positron.
  - Circumference 3km
- Aiming for the highest luminosity in world, we have adopted a nanobe scheme
  - Squeezing βy* with nano-beam collision scheme (x20)
  - Twice beam current of KEKB (x2)
- Recorded a peak luminosity

  twice that of KEKB.



	KEKB achieved		SuperKEKB 2022/6/8	
	LER	HER	LER	HER
Ibeam [A]	1.673	1.188	1.321	1.099
# of bunch	1585		2249	
Ibunch [mA]	1.033	0.7495	0.5873	0.4887
βy*	5.9	5.9	1.0	1.0
Luminosity[$10^{34}cm^{-2}s^{-1}$]	2.11		4.65	

SuperKEKB Beam Instrumentation System

System	Quantity		
	HER	LER	DR
Beam position monitor (BPM)	466	444	83
Displacement sensor	110	108	0
Transverse bunch feedback system	2	2	1
Longitudinal bunch feedback system	0(1)	1	0
Visible SR size monitor	1	1	1
X-ray size monitor	1	1	0
Beamstrahlung monitor	1	1	0
Betatron tune monitor	2	2	1
Beam loss monitor	207		34
DCCT	1	1	1
CT	1	1	0
Bunch current monitor	1	1	1

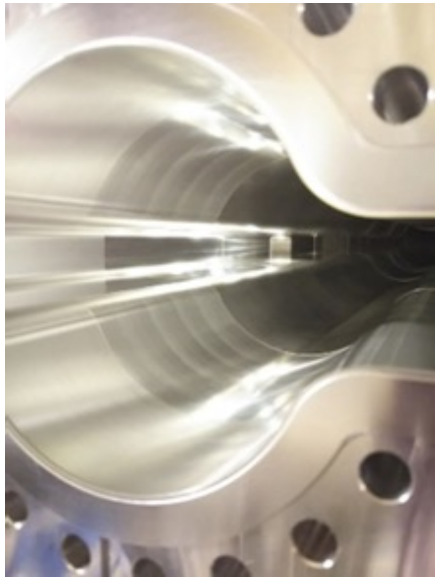
Synchrotron Radiation Monitor

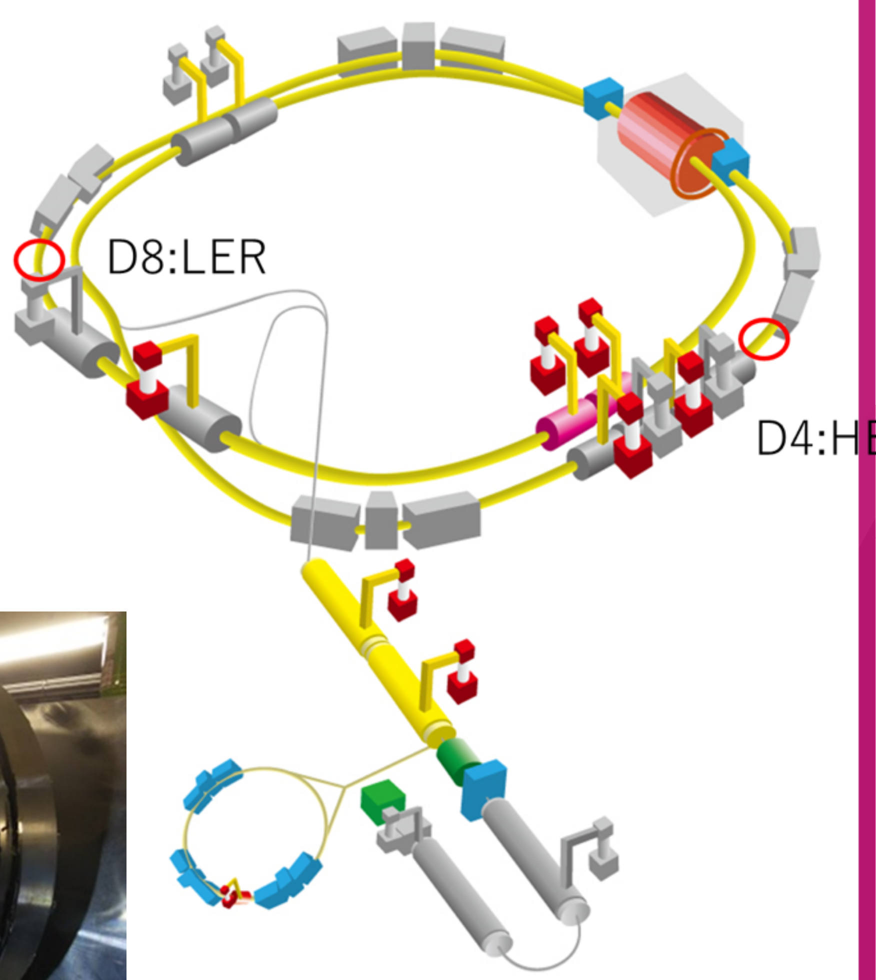
Diamond mirror

Coronagraph

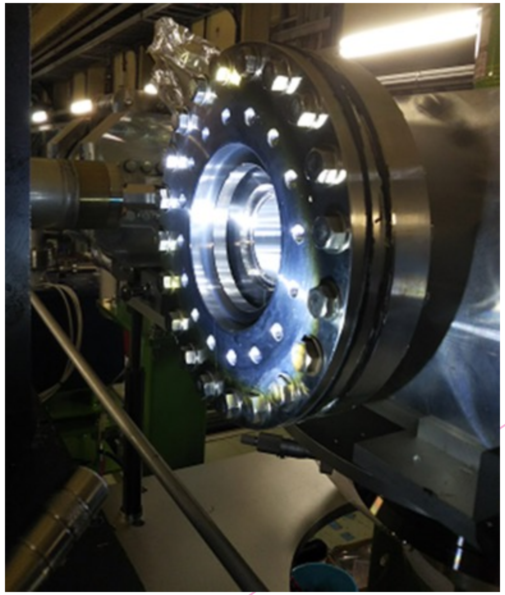
Injection beam measurement

Synchrotron Radiation Monitor(SRM)





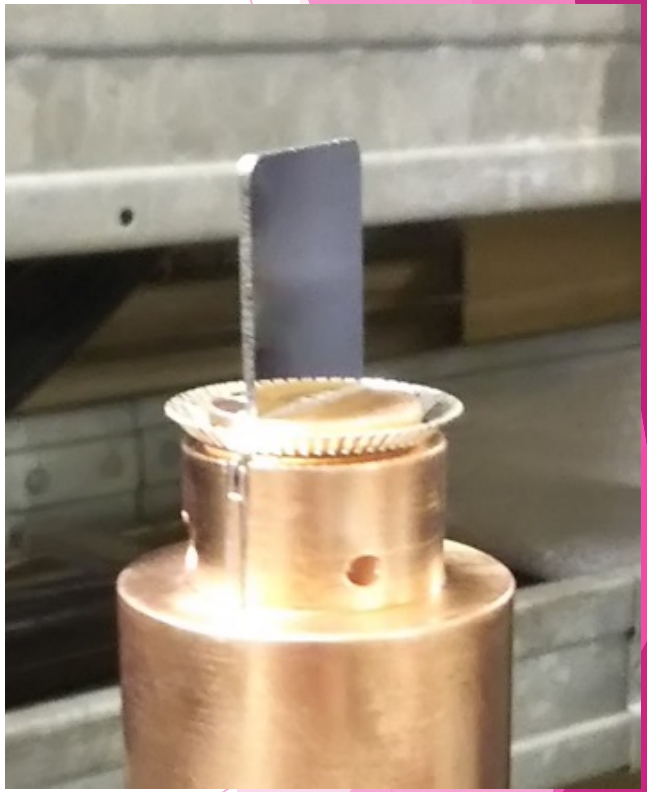
- We take emission light out of the bending magnet that set in last part of the arc section.
- Extraction chamber
  - Set up to downstream 23 m of source bend magnet.
  - Diamond mirror is inserted
  - Optical window



SRM 1: Diamond Mirror

- An extraction mirror of visible light is made of diamond to suppress the thermal deformation.
- Developed a single crystal diamond mirror and made efforts to suppress the current dependence of thermal deformation, but the mirror had not only the current dependence of the deformation at high currents, but also some deformations made during manufacturing at beginning of SuperKEKB.
- Made a new thick polycrystalline diamond mirror that is not easily deformed by heat and installed it in 2020.
  - Resistance to thermal deformation is similar to single crystal.
  - Reflectance is high because the coating is changed from gold to platinum.

⇒ obtain a sufficient amount of light for beam profile measurement for each bunch, and it became possible to measure the beam halo and injection beam for each turn.



SRM 2: Coronagraph

- Beam halo may cause unexpected beam loss or long-term irradiation leading to luminosity degradation and damage to accelerator components.
- Understanding and hopefully lowering beam halos have been attempted in high-power and/or high-luminosity accelerators.
- Our challenge: non-invasive measurements with sensitivity better than 1e-5.

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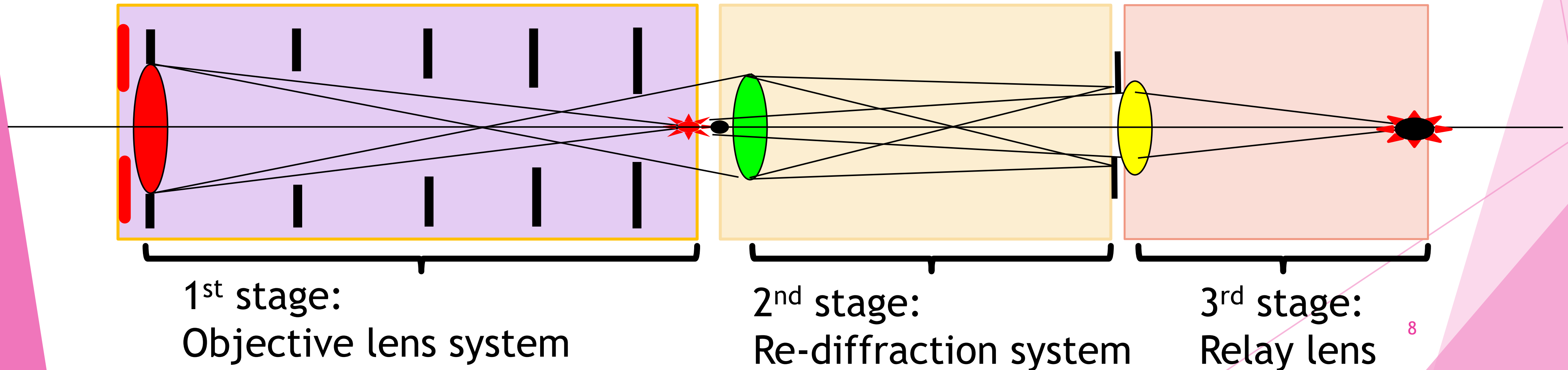
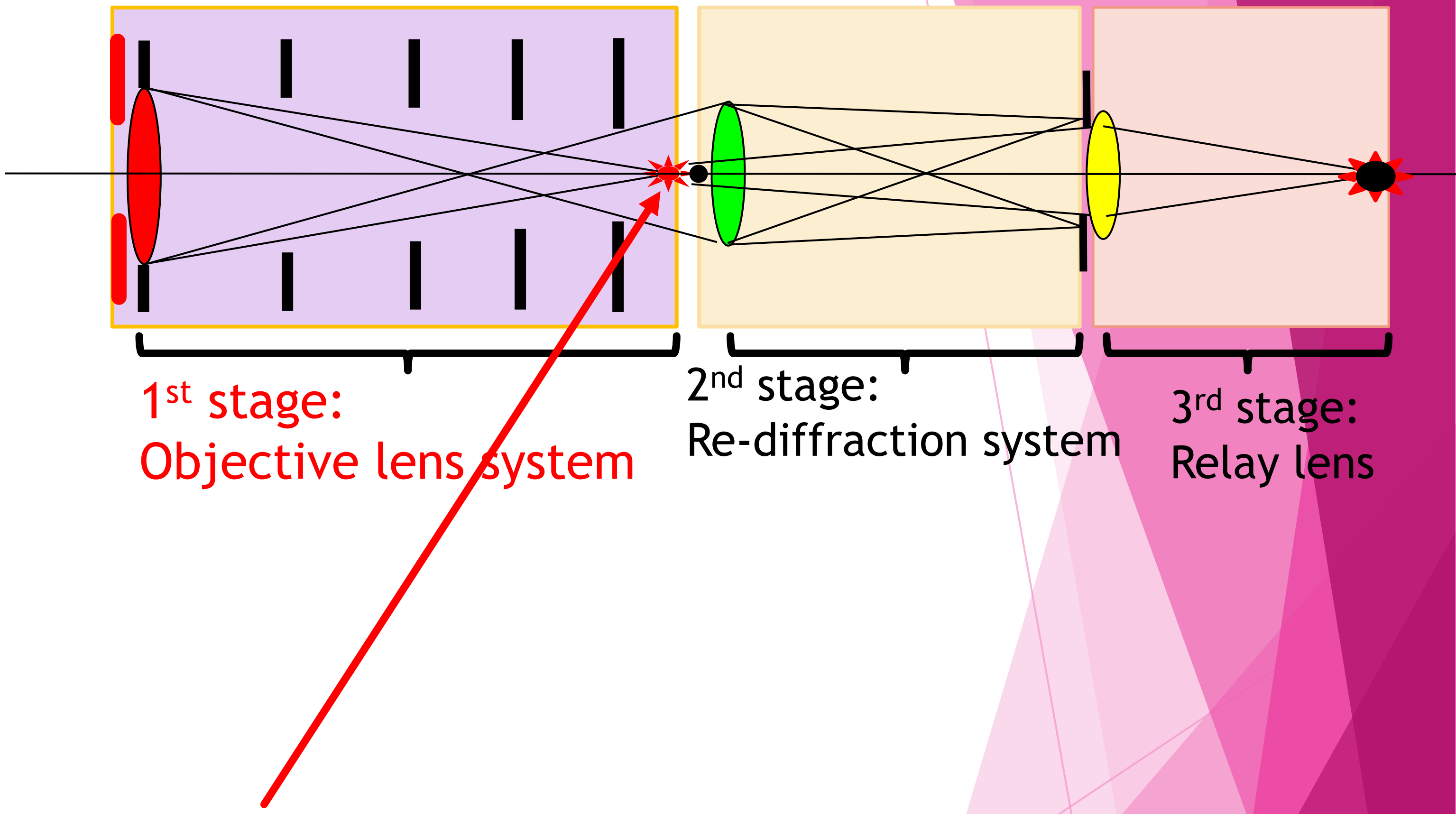
Introducing Coronagraph to SRM



Beam image and diffraction fringe (l=500nm)

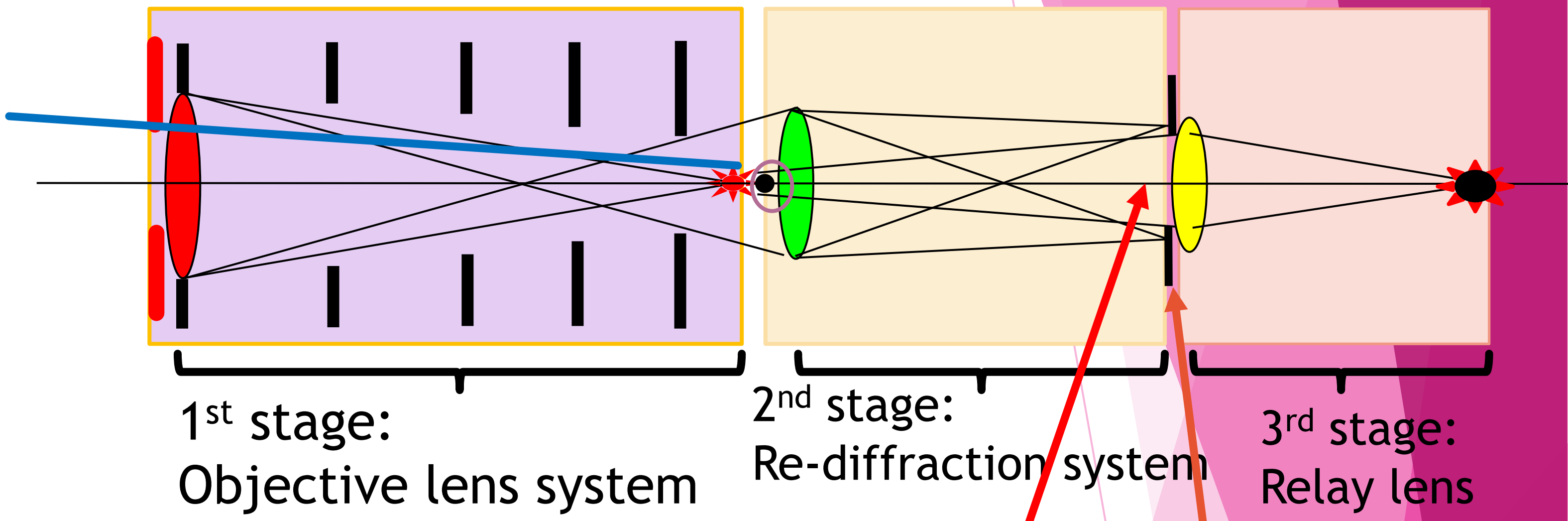
To eliminate a chromatic aberration, the 1st system adopts a reflective mirror system rather than a refractive lens system.



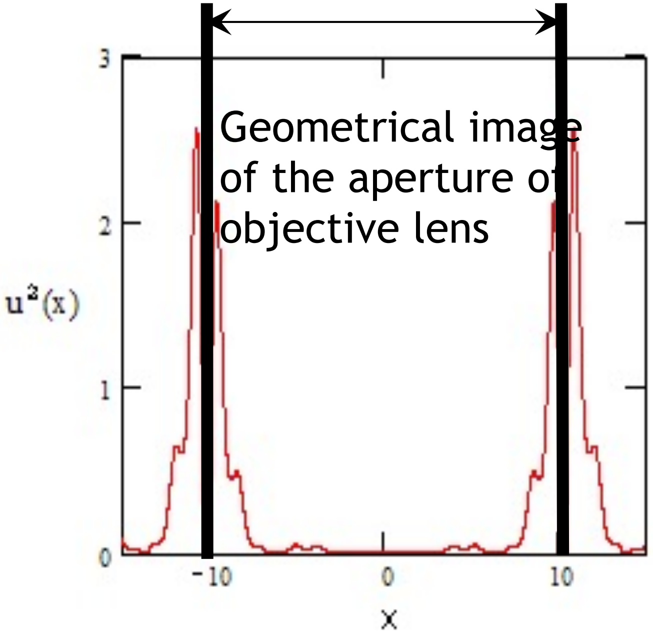
Clearly observed ~18th order fringes

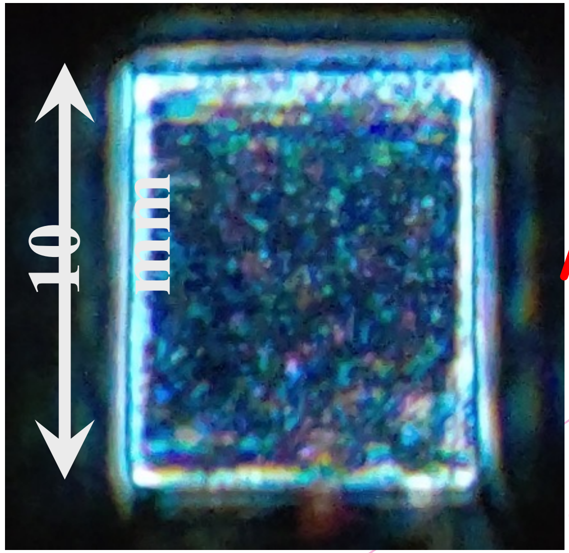
Diffraction image on the Lyot stop

- Input opaque disk to hide beam core.
- Diffraction fringes of objective lens aperture is shown.



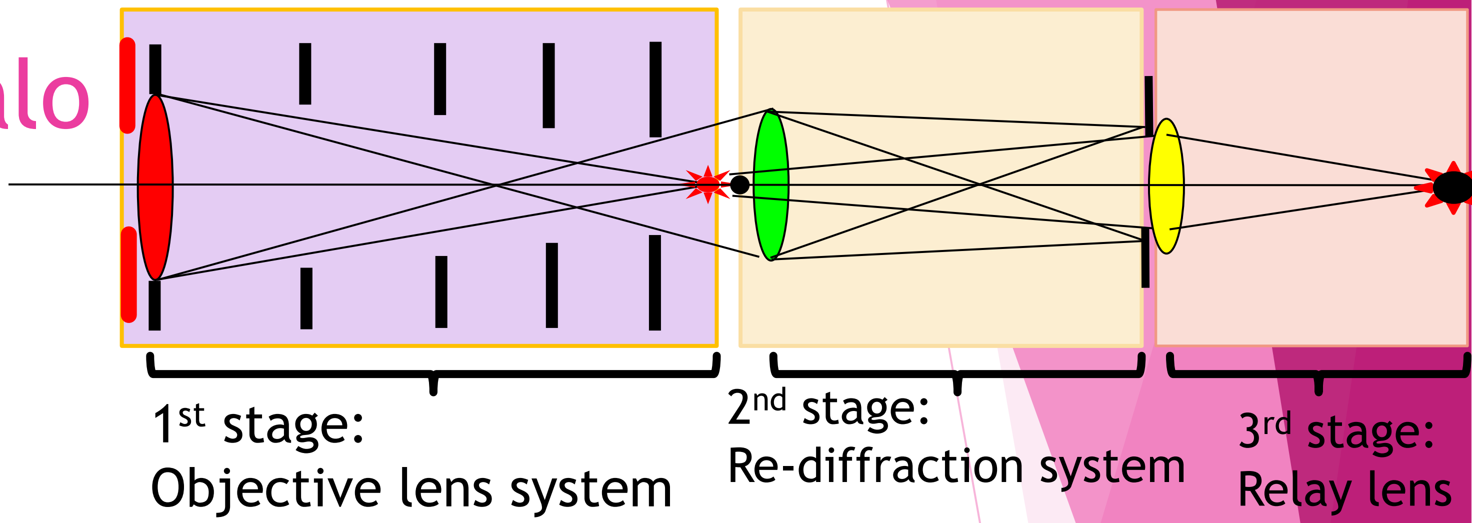
blocked by the Lyot stop



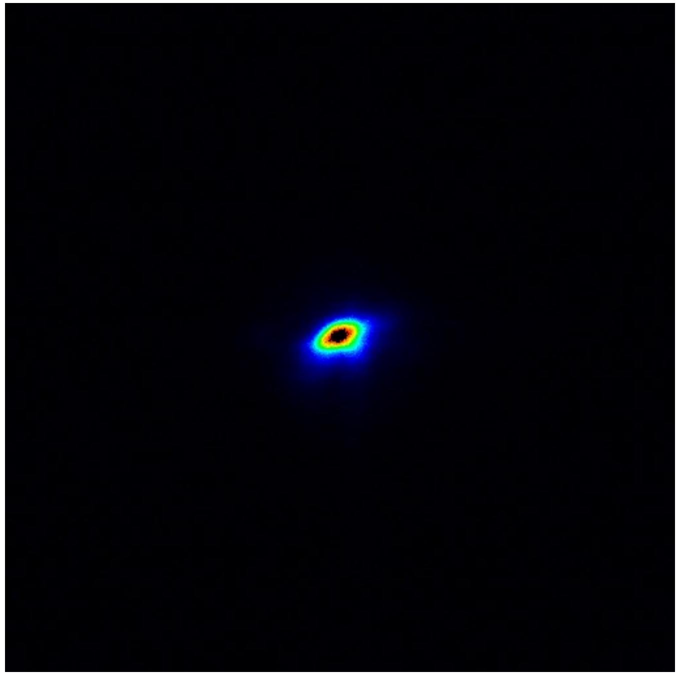


Observed image

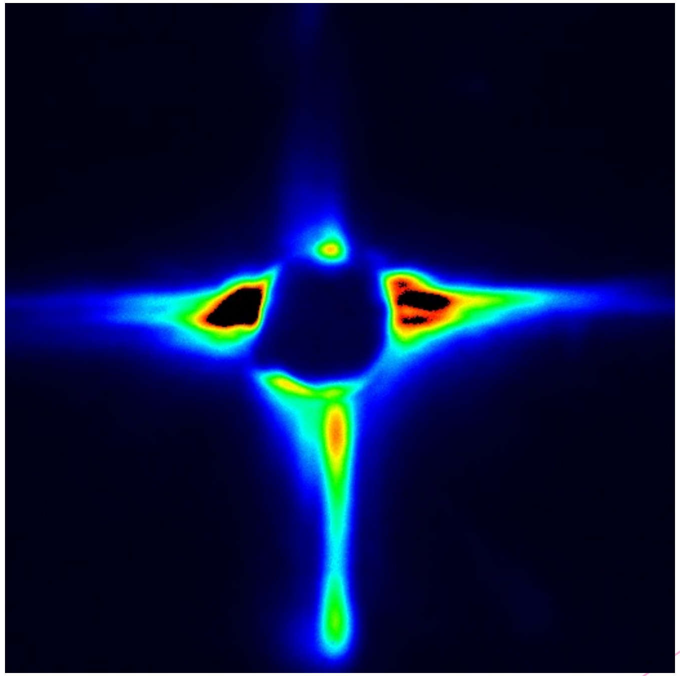
Observation of beam halo



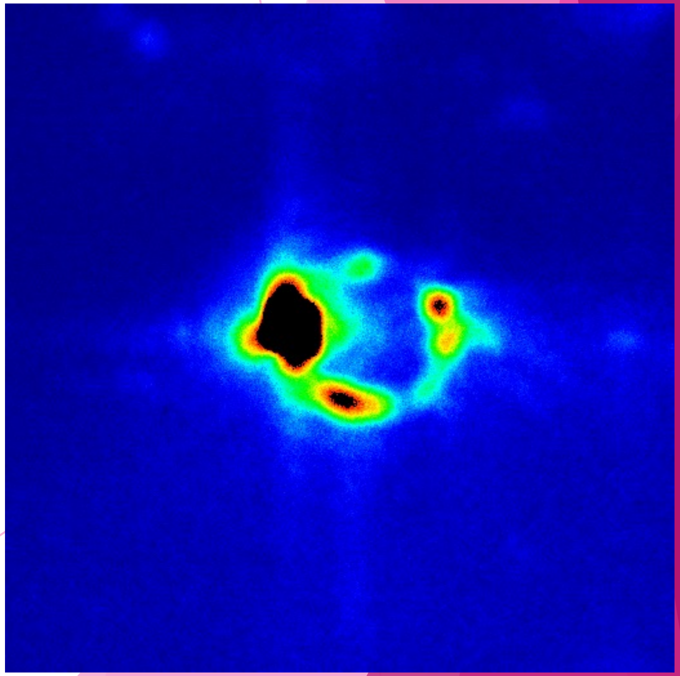
Beam core



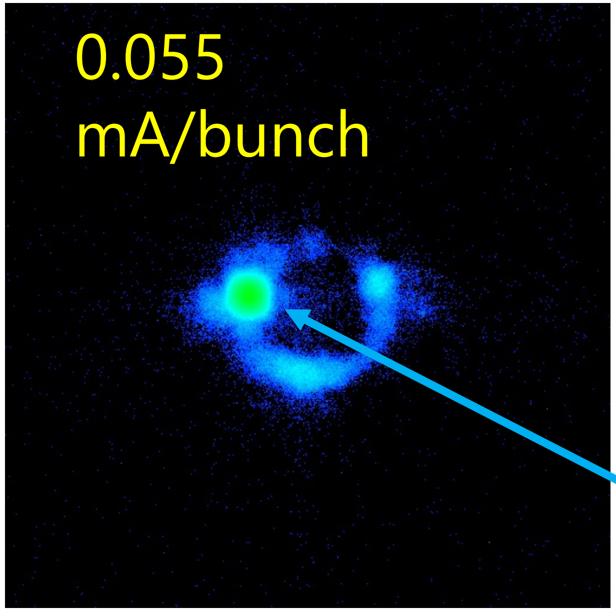
Core blocked by a Φ3mm disk

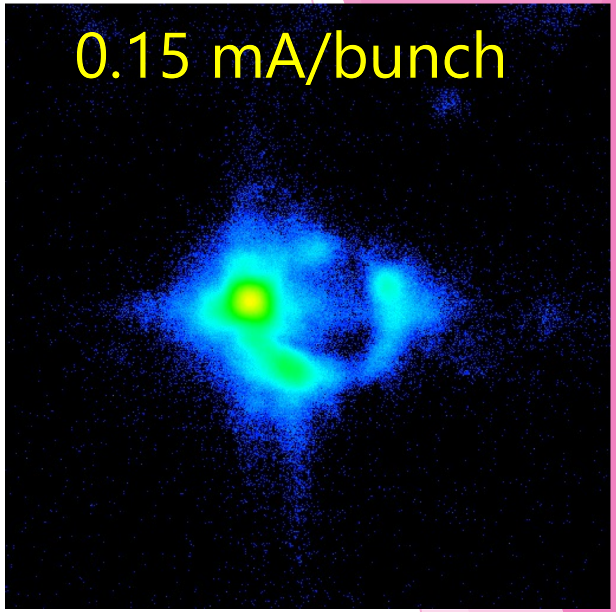


Re-diffraction fringes blocked by the Lyot stop

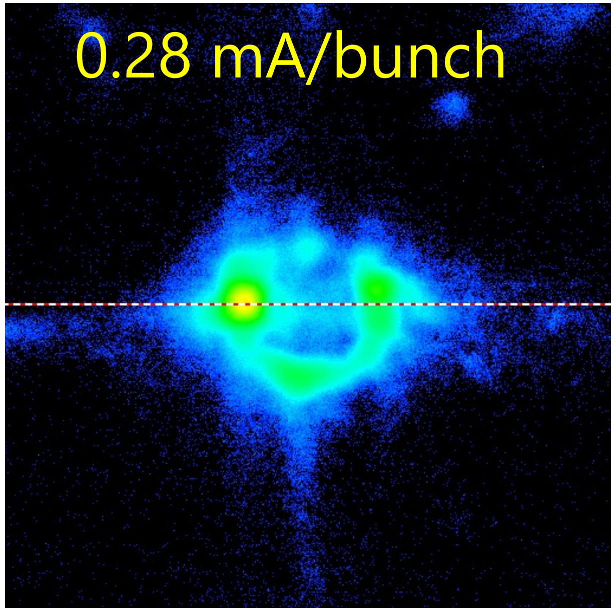


Observation : Bunch-current dependence in HER



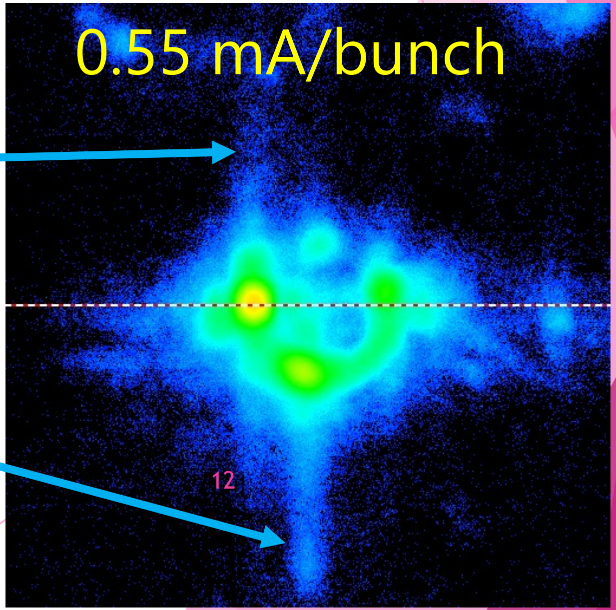


Due to beam orbit changes



Diffraction fringes made by the latter optics than the Lyot stop

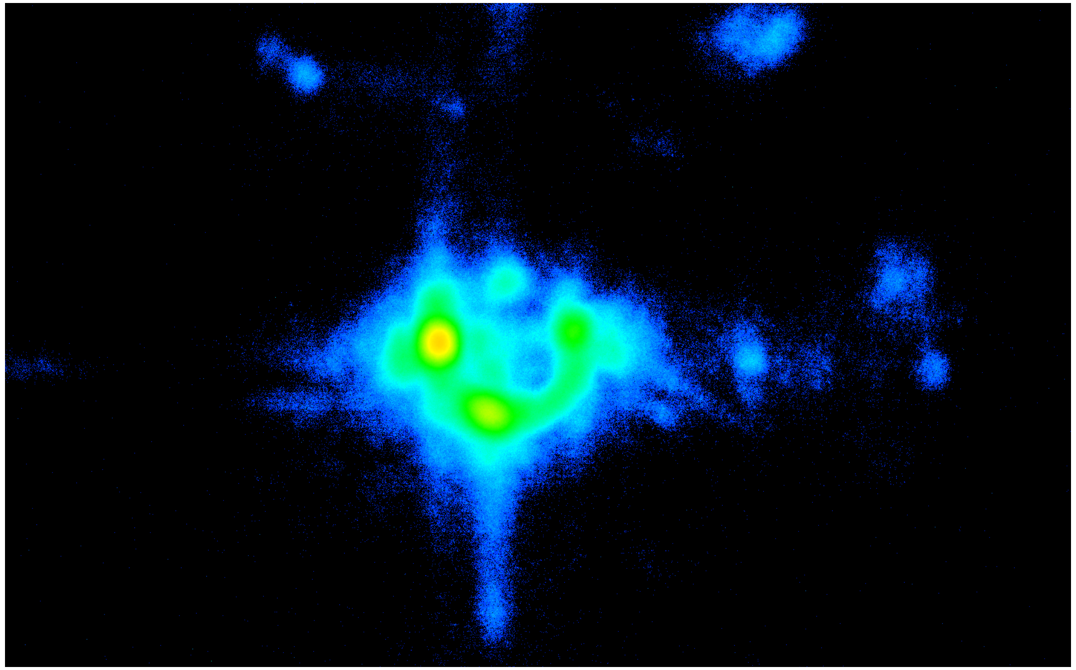
Leakage of diffraction fringes by the diamond mirror

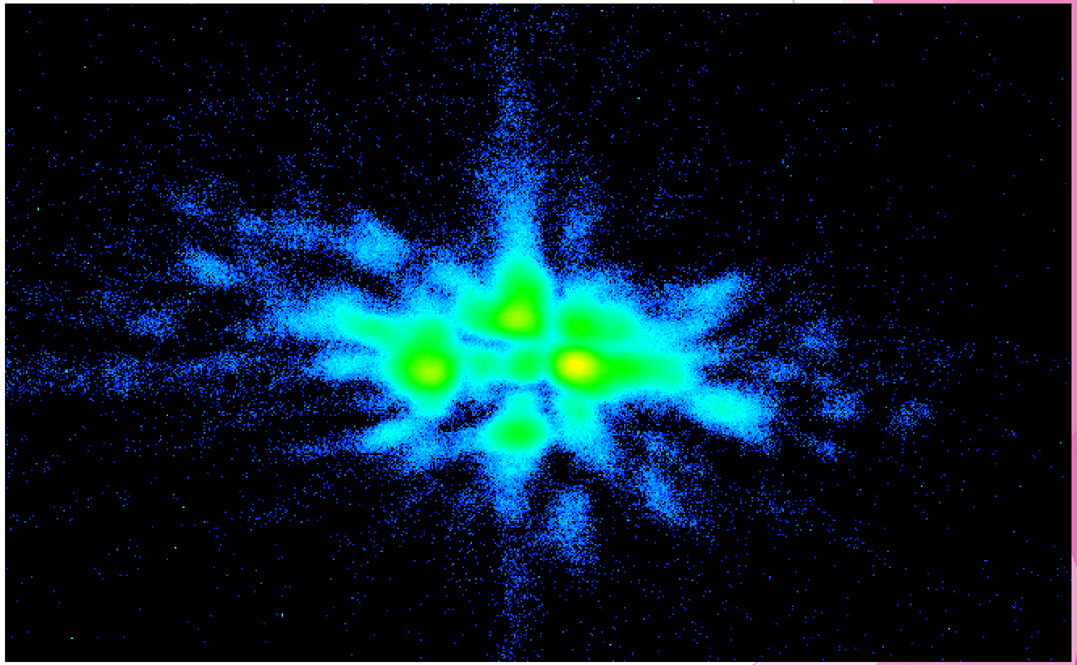


Comparison of halos between HER and LER

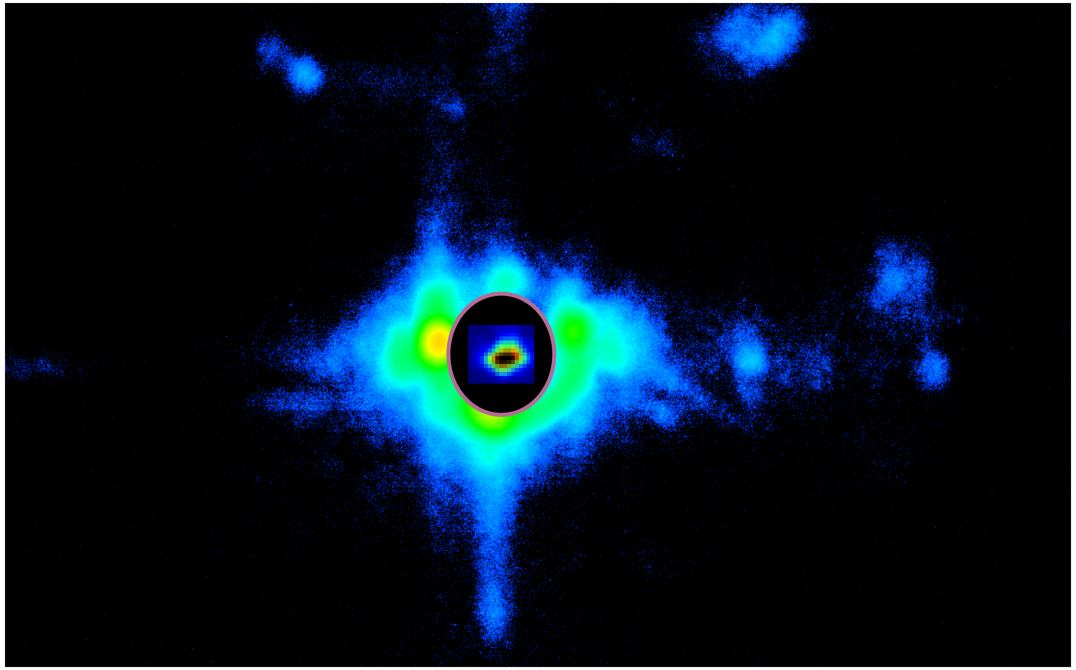
Gate width 10msec

HER 0.57mA **LER 0.61mA**

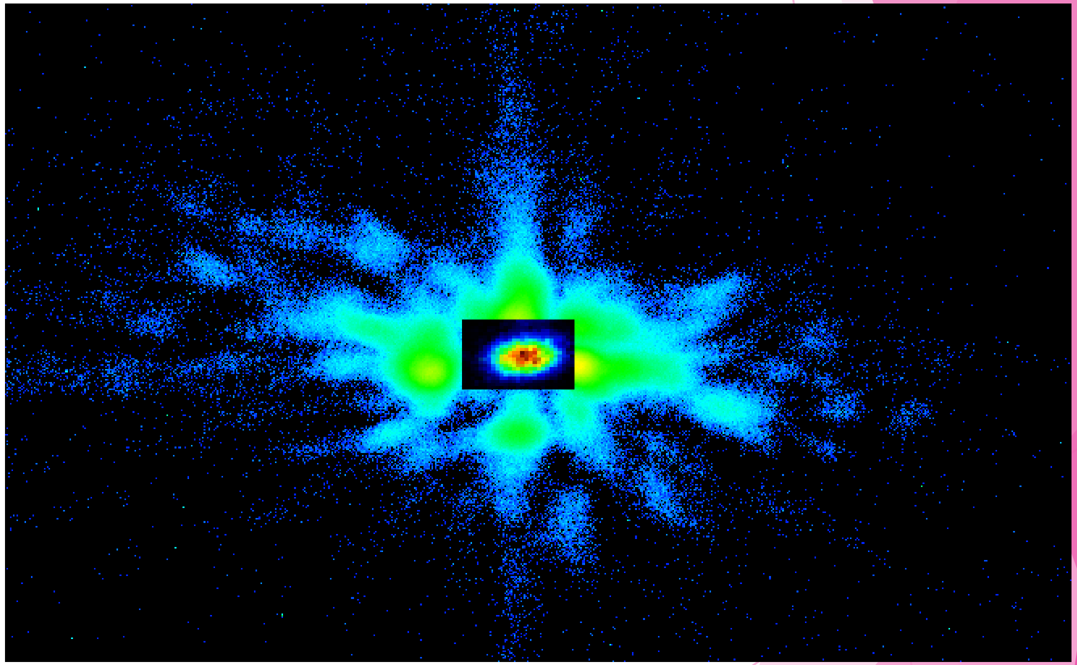




HER 0.57mA

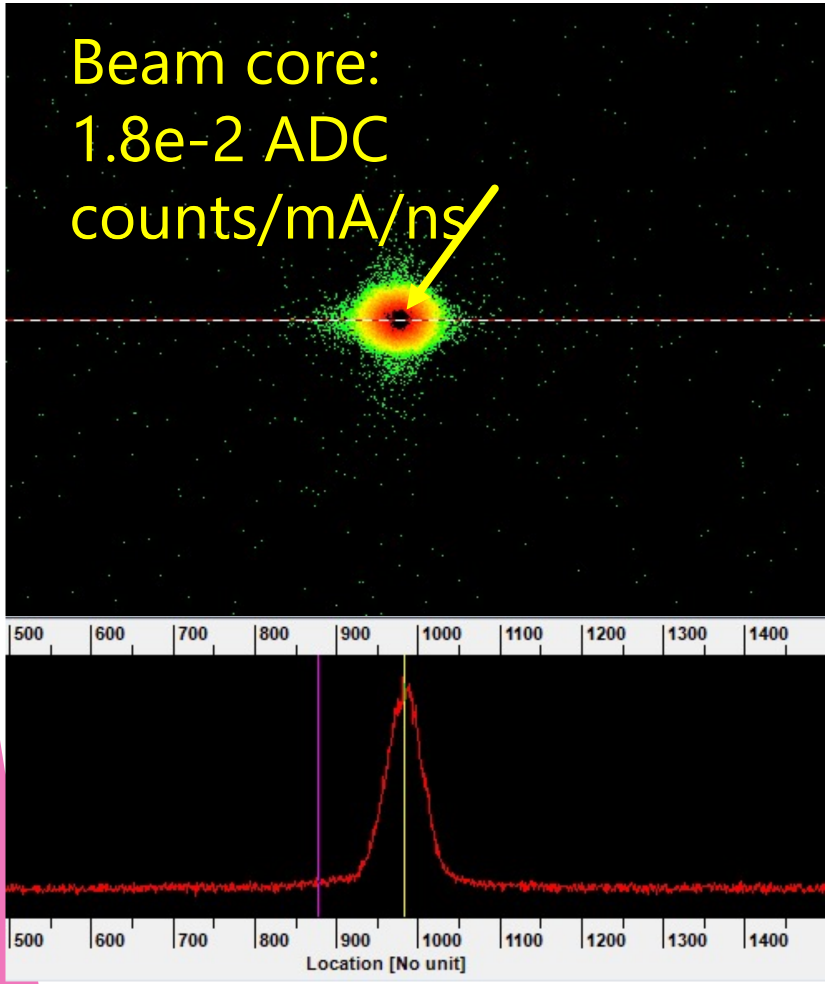


LER 0.61mA

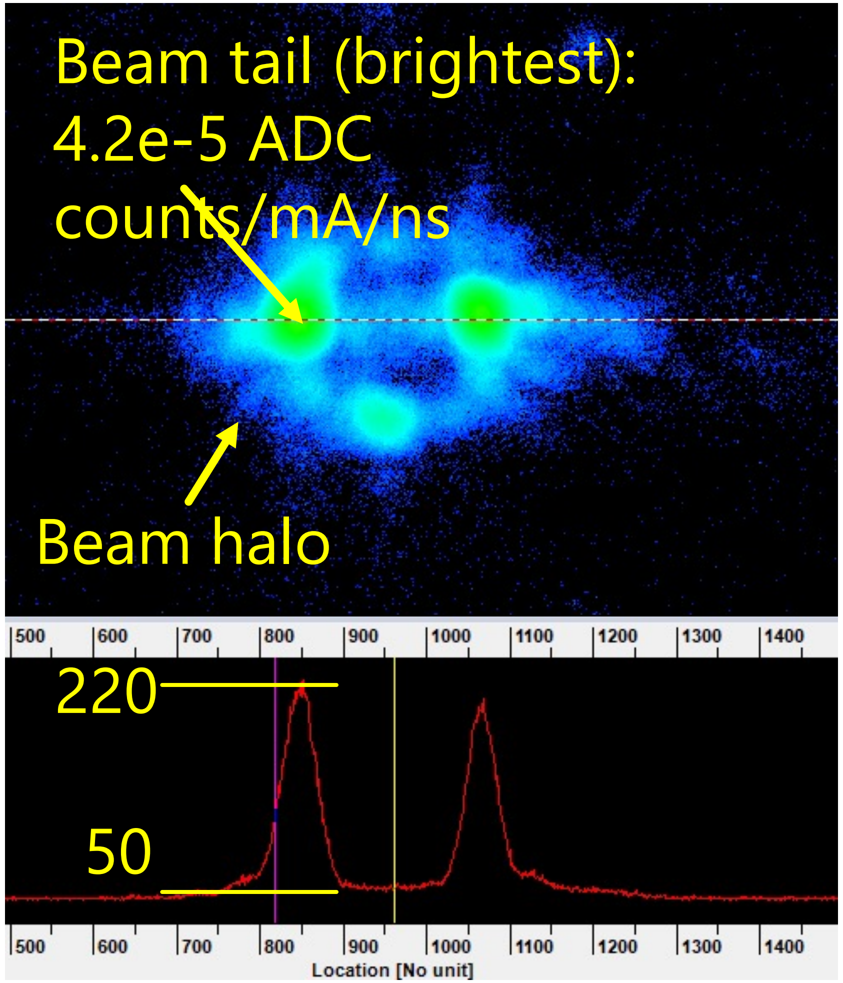


Sensitivity in beam halo measurement

τ = 10 ns



τ = 10 µs



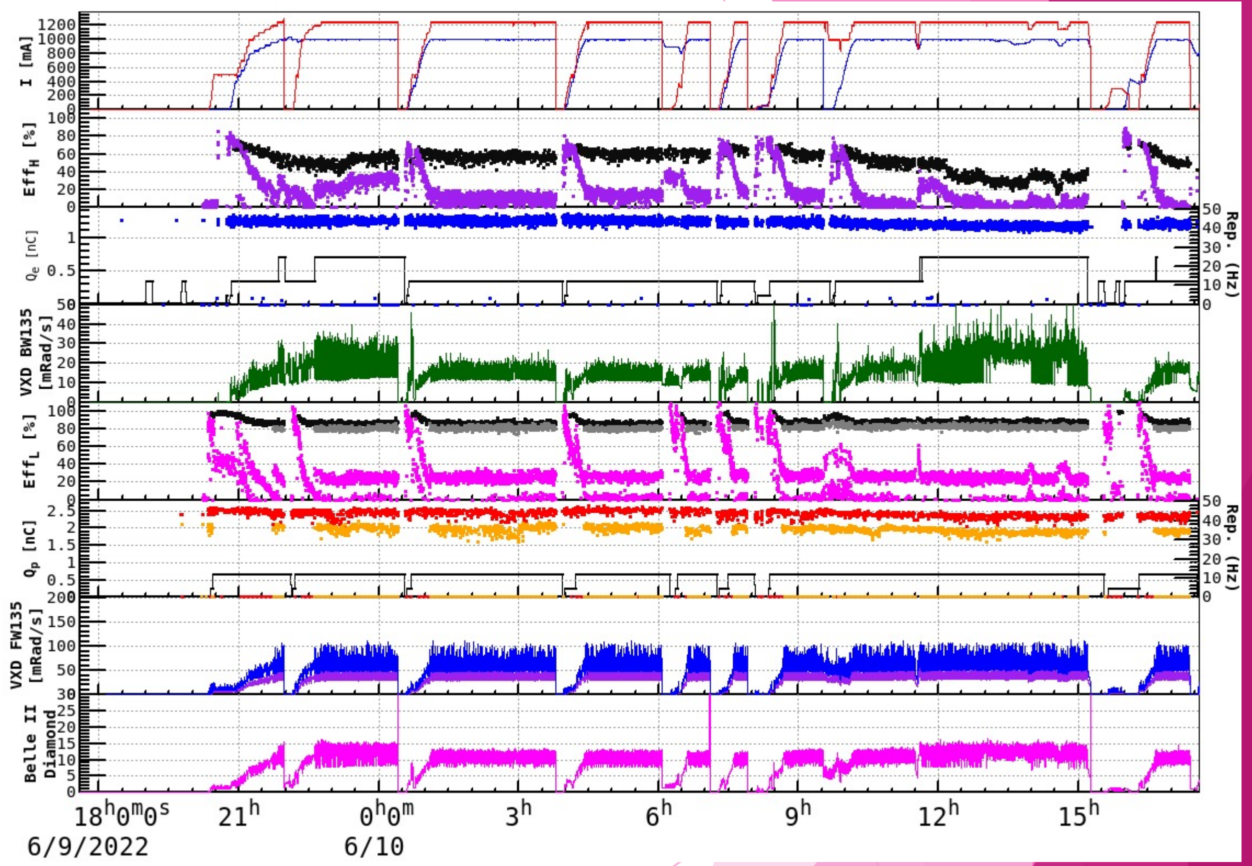
Ratio of Brightest tail/Core
~ 2e-3

Extending the exposure τ to have a brightest spot 12 bit max. counts and looking at beam halo (few counts + ped.),
the beam halo/brightest ratio
~ 4 ADC counts/12 bit counts ~ 2e-3

Ratio of beam halo/Core ~ 2e-3 x 2e-3 ~ O(1e-6)

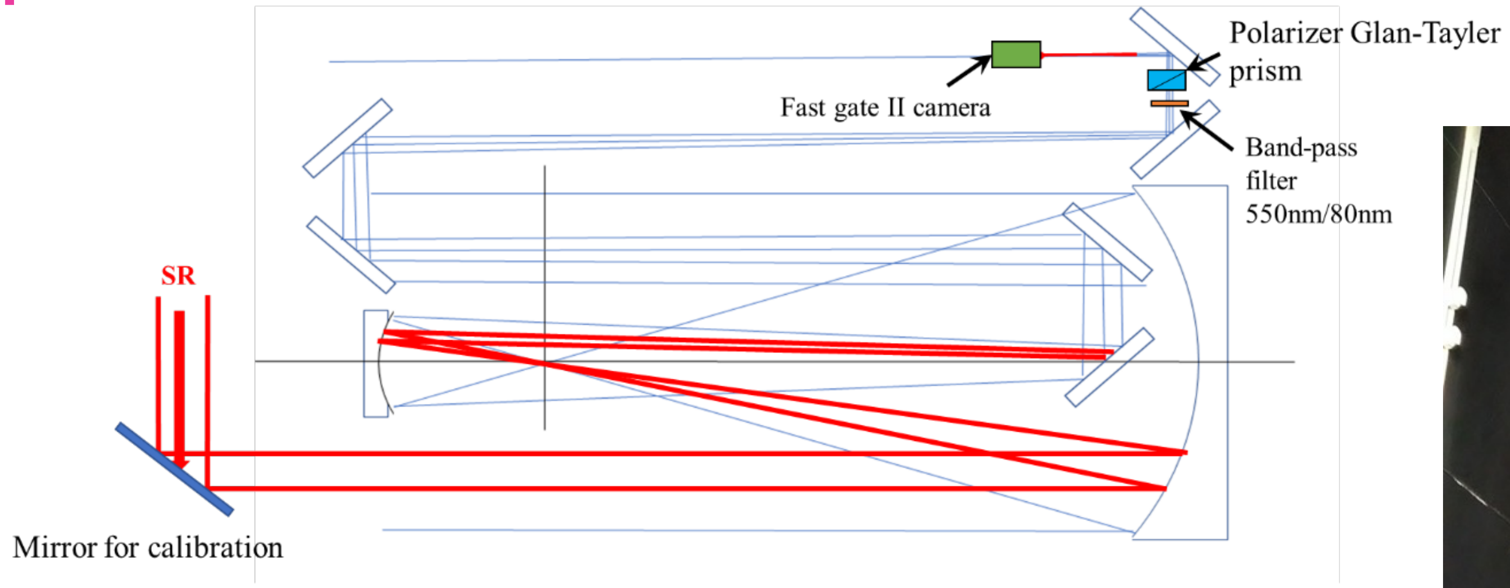
SRM 3 : Injection beam measurement

- When the injection efficiency becomes unstable, it becomes difficult to accumulate the beam and the background to the detector increases, which interferes with physics experiments.
- It is important to observe how the injection beam turn in the ring usually and prepare for the measurement of difference with worth efficiency injection beam.
- Since it became possible to measure the beam for bunch by bunch, we tried to see the state of the injection beam.



Relationship between injection efficiency and background

Injection Beam Measurement :Setup

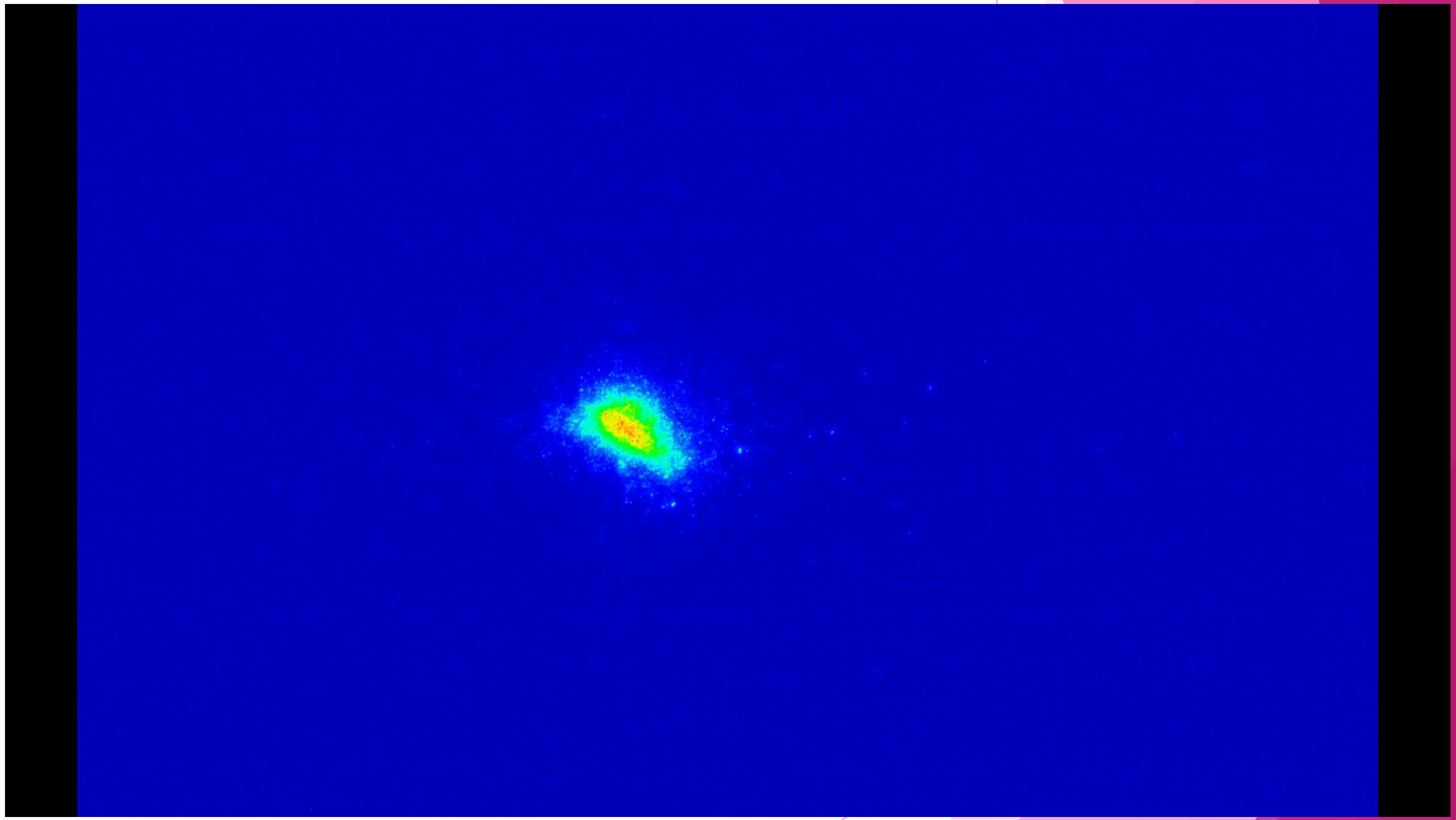


- Object system which designed for coronagraph is used to measure the injection beam.
- Single-turn injection was applied on the HER beam. (Each injection bunch kicks out the previous injected bunch. Then the ring always has only one bunch).
- Measure the beam shape for each turn after injection by using gated camera.

Injection Beam Measurement Result : HER injection beam

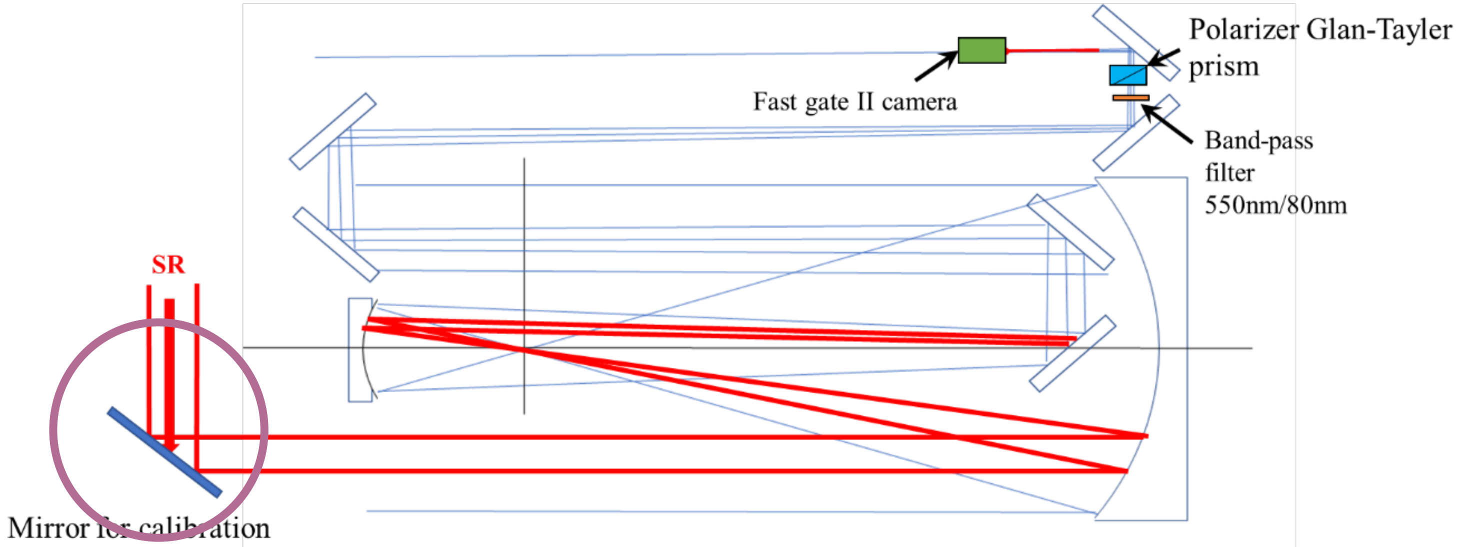
- Gate width : one turn (10μs).
- Trigger was applied at the injection timing
- After finding the first turn, the beam behaviour was observed turn by turn.

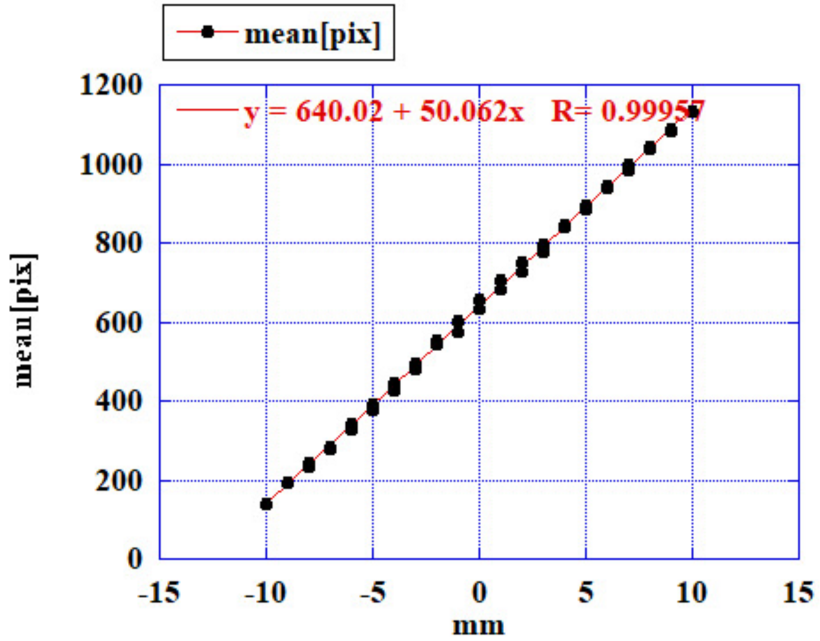
- The beam just after the injection repeatedly oscillation.
- Since SuperKEKB operating tune is close to a half-integer, it can be seen that the bunch moves left and right at every turn.
- The beam size does not shrink monotonically, but shrinks while repeating oscillation.



Injection Beam Measurement : Calibration

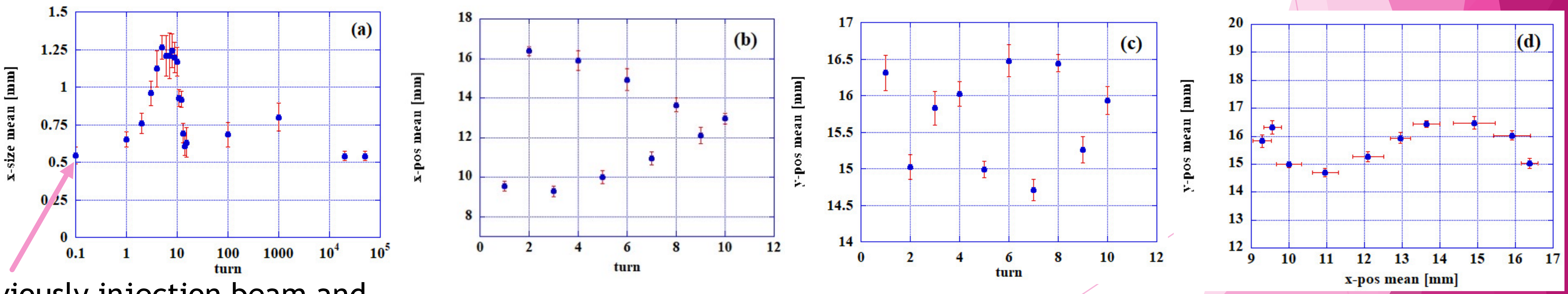
- The mirror was placed on a cross roller stage equipped with a micro-meter and moved horizontally by ± 15 mm to measure the position on the screen. This corresponds to moving the beam virtually.
- Calibration was performed using a stored beam with the gate width of the gated camera reduced when the beam was stable.
- The error bars due to measurement variability are smaller than the plot, and the variability of circles at the same position comes from the displacement of the beam due to the difference in measurement time. No large distortion is seen on the photoelectric surface of the CCD camera.





Injection Beam Measurement Result : HER injection beam

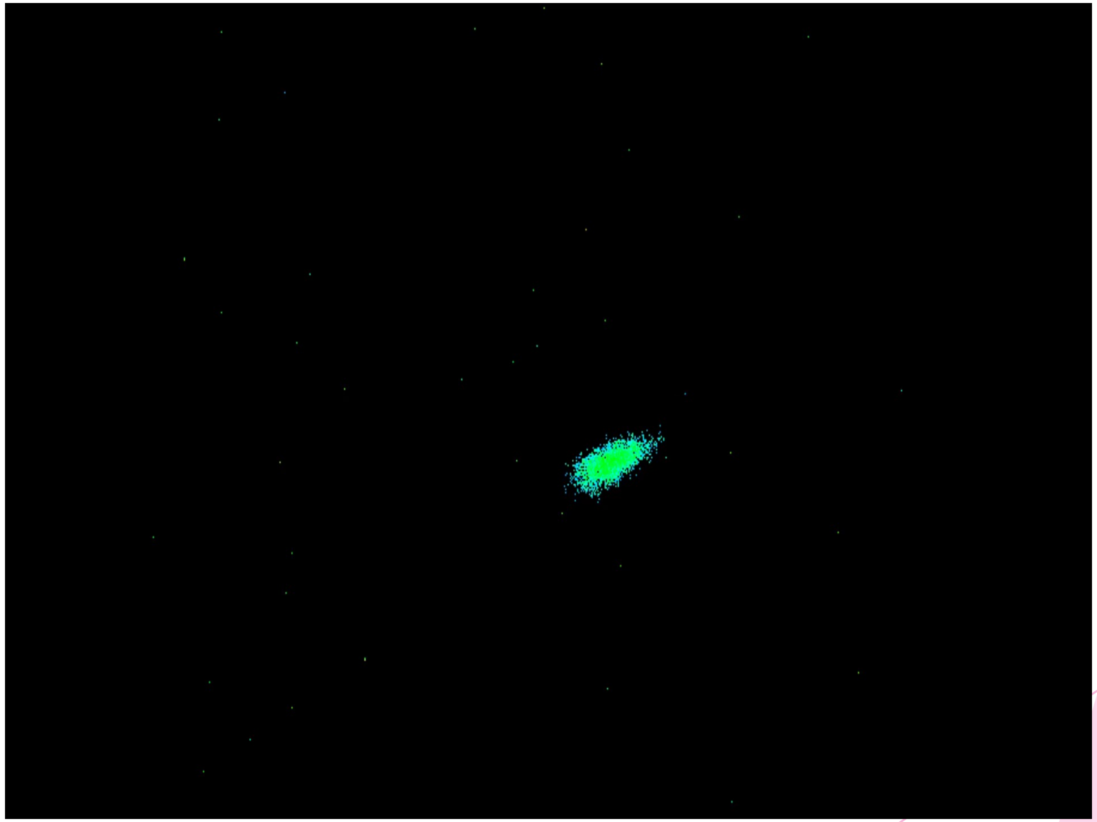
- Horizontal beam size for each turn of the injection beam after calibration.
  - The injection beam repeatedly expands and contracts and damped after 10,000 turns (10 ms).
  - The beam size is including the diffraction effect.
- The injection beam oscillation
  - it can be seen that the amplitude becomes stable while oscillate with a width of about ± 4.5 mm at the maximum.



previously injection beam and corresponds after a complete dump for comparison

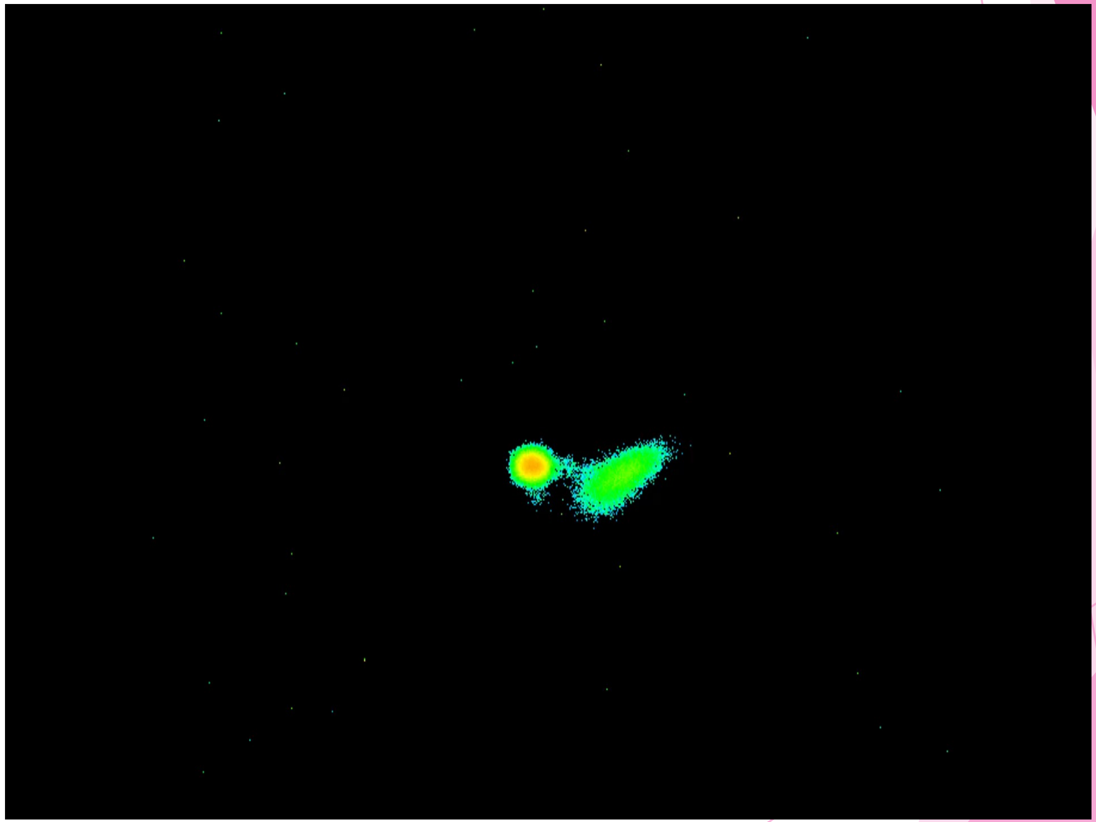
Injection Beam Measurement Result : LER injection beam

The LER Injection beam also expands and shrinks once while oscillation like the HER.



Injection Beam Measurement Result: with stored beam

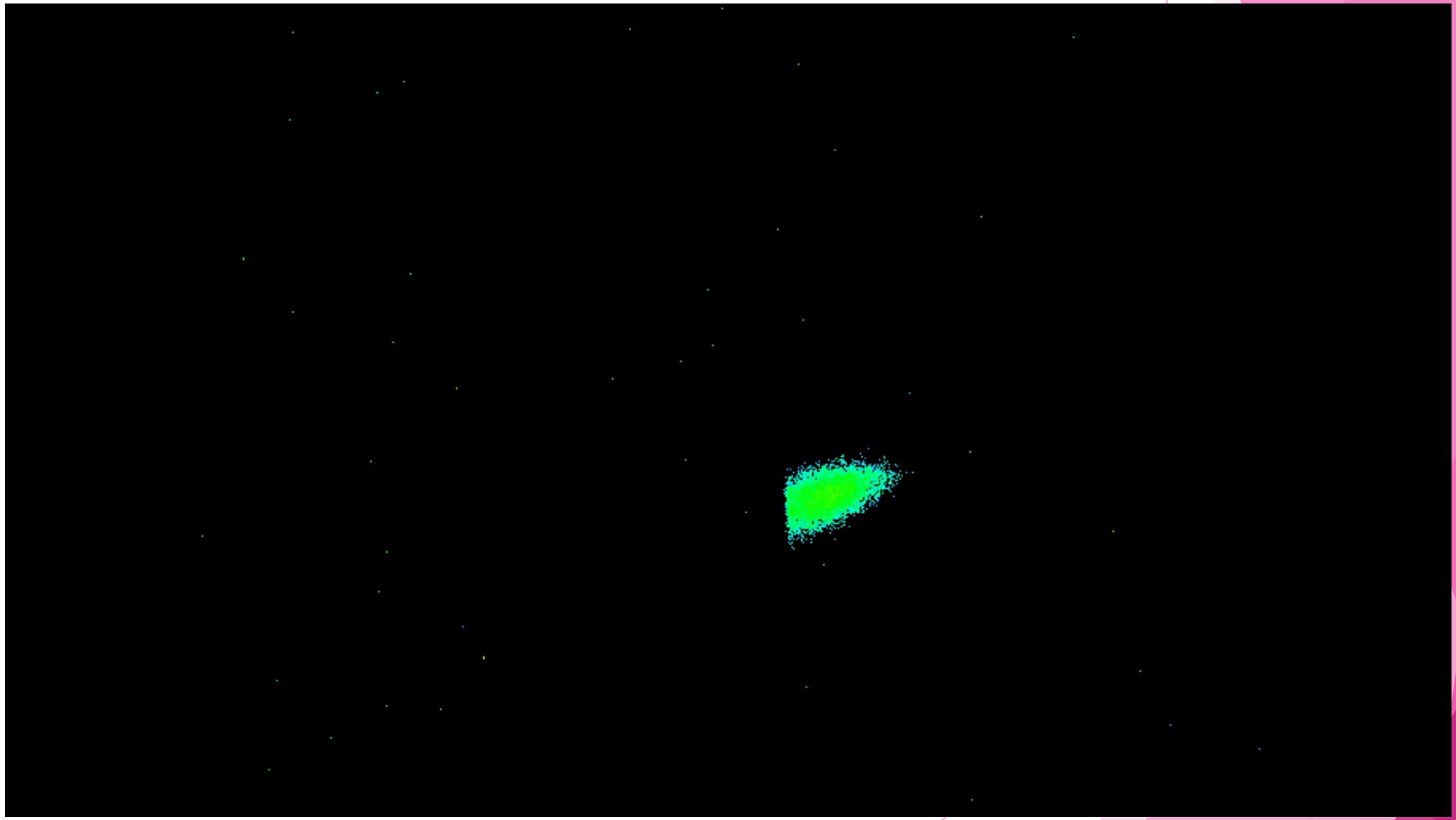
We also observed the injection beam when stacking normal collision beams.



Injection Beam Measurement Result : masked stored beam

In order to see the injection beam during the collision, we put a mask in front of the camera to hide the stored beam.

Some measurement is possible.



SRM : Summary

- By exchanging the light extraction mirrors for both the electron ring and the positron ring, the image of the beam can be clearly focused, and the smaller charge beam can be measured turn by turn.
- We developed coronagraphs in SuperKEKB enabling non-invasive and high-sensitivity measurements for beam halo.
  - Some beam halos are observed in both HER and LER,
  - Halos in HER and LER are not same.
  - Sensitivity was ~O(1e-6) compared with the beam core.
- We prepared a system for observing the behaviour of the injection beam in the ring when the injection efficiency becomes unstable.
  - It was observed that the injection beam size was dumped while oscillating even when the beam condition was stable.
  - The reference data was measured in the study mode, which can measure only the injection beam in a single turn injection and by masking the stored beam, it is possible to measure some injection condition even during collision operation.

Beam Loss Monitor

Loss Monitor System

Abort system

Sudden beam loss

0. Loss Monitor System

- How can we protect the hardware components of the detector and the accelerator from the damage caused at high beam currents ?

↓

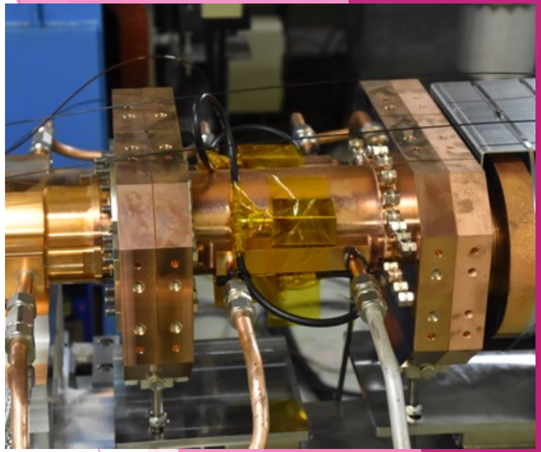
1. Abort the beam as soon as possible when the abnormal situation happen.
   → "**Abort System**"
2. Investigate the cause of abnormalities in the beam and deal with them.

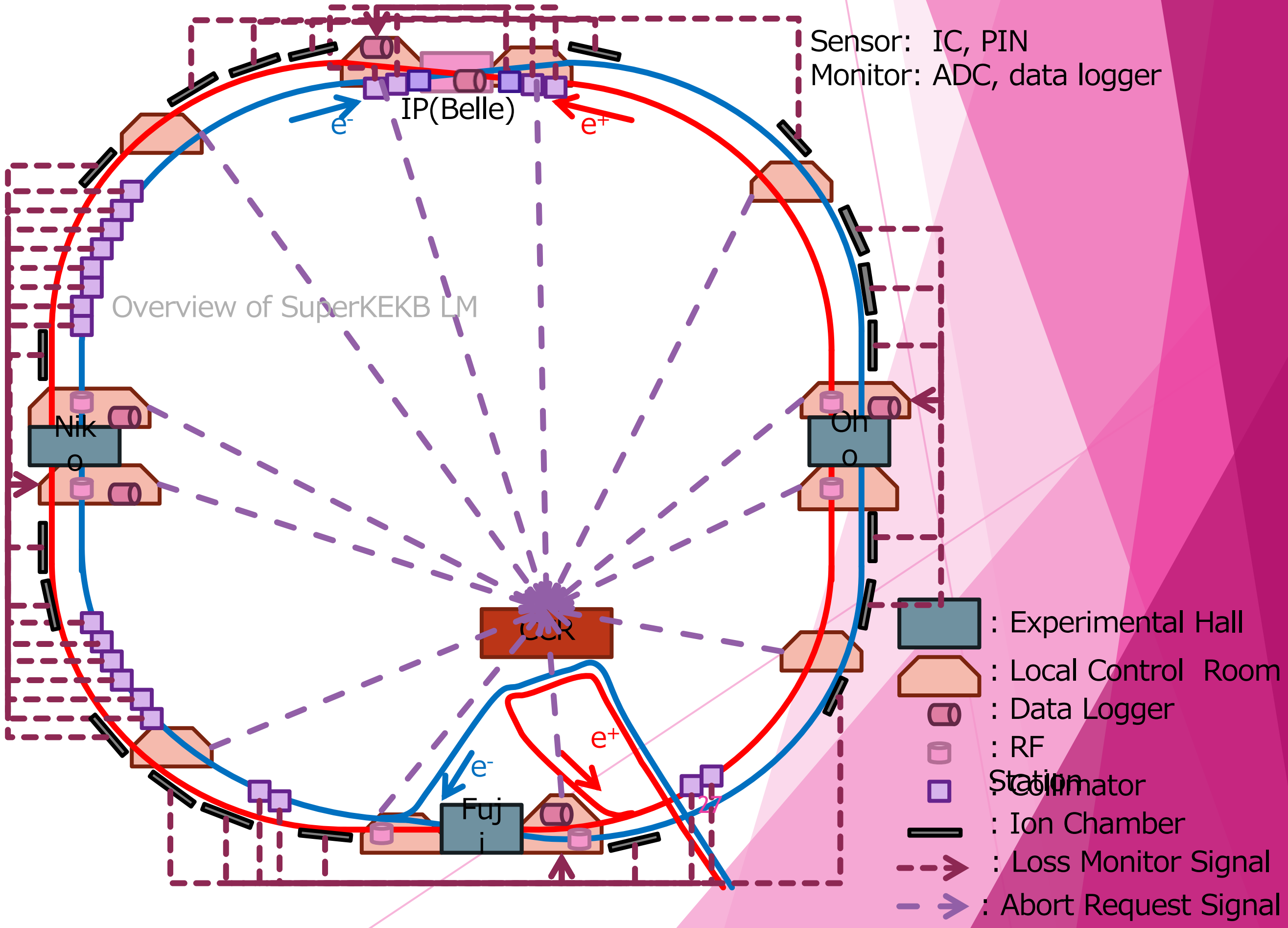
   → "**Sudden Beam Loss**" analysis

In both cases, a combination of loss monitors and other monitors can help.

Loss Monitor System

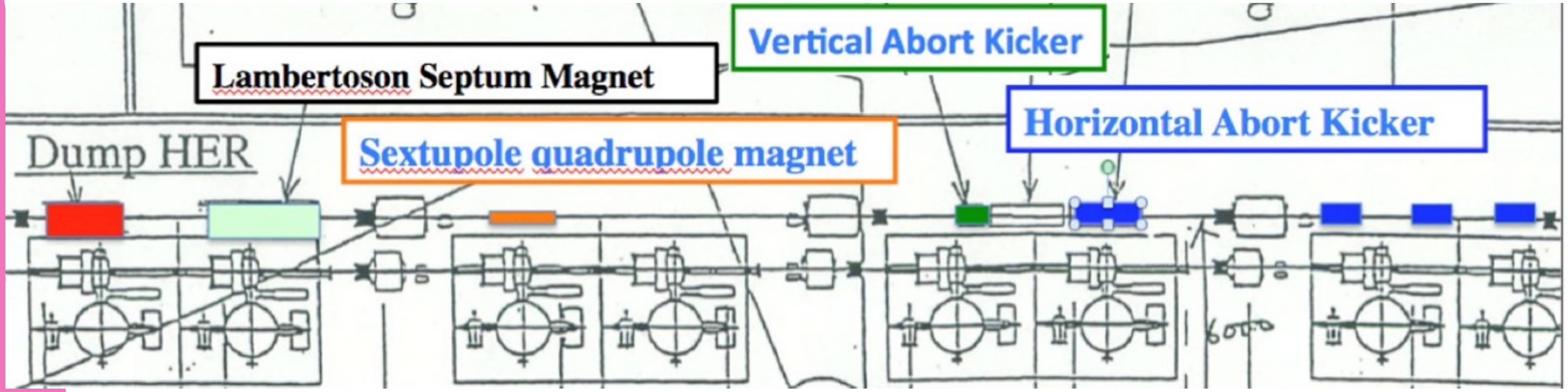
- Measure the beam loss
- Used for
  - triggering the beam abort kicker
  - tuning and analysis of the beam operation
- No. of Sensors : 200
- Ion Chamber: Cover a wide range in space.
  - Put to cable lack of all over the tunnel to cover a wide range in space.
  - Free Air Ion Chamber (20D co-axial cable)
- PIN photo diode: Fast response and identify the ring in which the beam loss occurred.
  - Trigger generation time for beam abort in integrator : <2μs
- Optical Fiber ←New !





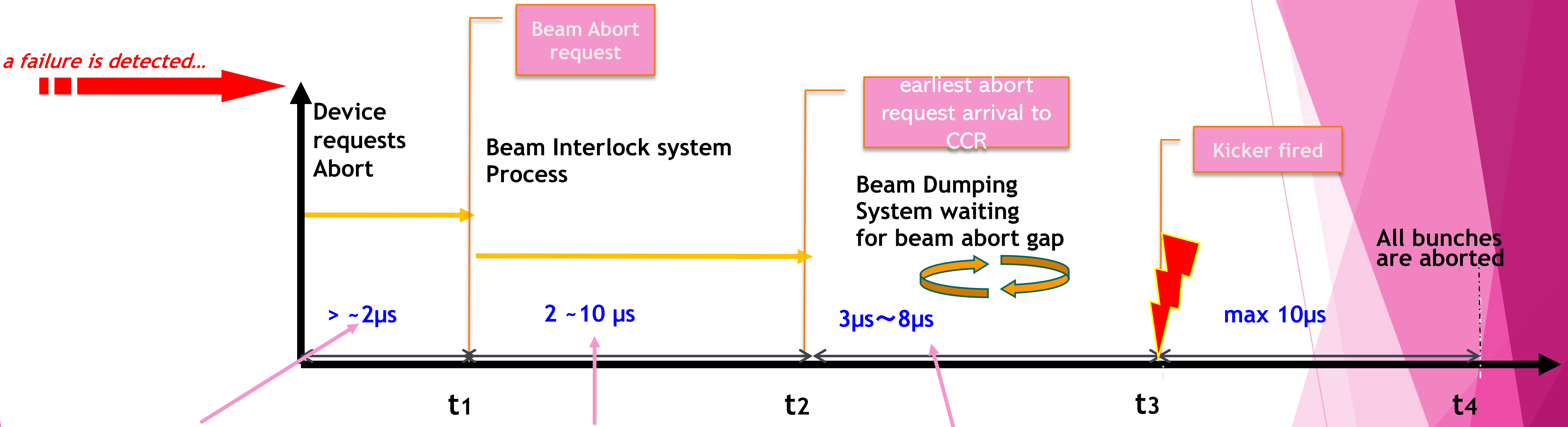
1.Abort System

- In order to protect the hardware components against the high beam currents, we installed the controlled abort system.
- The beam is kicked by an abort kicker, taken out of the vacuum chamber through an abort window made of Ti, and throwed into a beam dump.
- Dumped beam length : one revolution time (10 μs).
- Build-up time of the abort kicker magnet : 200 ns (empty bucket space).
- Synchronization of the kicker timing and the abort gap is required for the protection of hardware.



Abort Trigger Delays

We minimized abort trigger time to protect the hardware damage.



Hardware dependent

To summarize the abort request on the beam abort system.

Depends on the optical cable length from the local control room to CCR.

Synchronization of the abort request signal with revolution/2 in FPGA. : Max delay=5μs
Delay to synchronize to the abort gap(fixed delay) : ～0μs
Delay from CCR to kicker (400m) : 2μs
Thyratron ON :1μs
Rise time for the kicker : 200ns

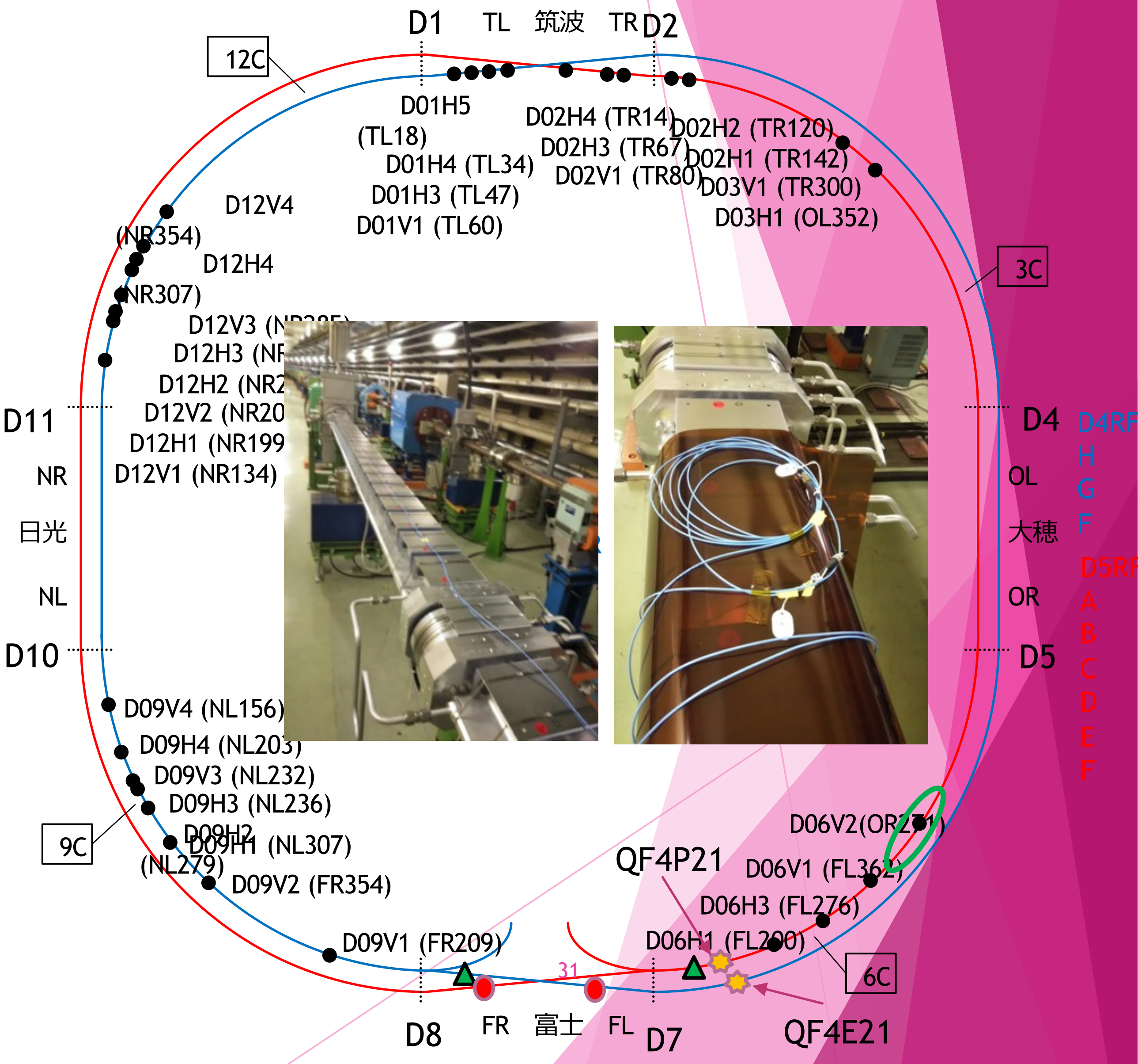
Minimum Abort Delay = 17～30μs

Minimize “Abort Trigger Delays”

- Introduced the injection veto system to PIN beam loss monitor for collimator to set lower threshold and the abort trigger can be issued quickly.
- Changed the signal route of the loss monitor installed at the downstream of one collimator that frequently issues abort triggers.→the abort trigger can be sent out earlier.
- Introduced new loss monitor near the abort kicker.
- minimized delay to synchronize to the abort gap.
  - removed unnecessary fixed delays
  - increased the abort gap in the beam train from one to two.

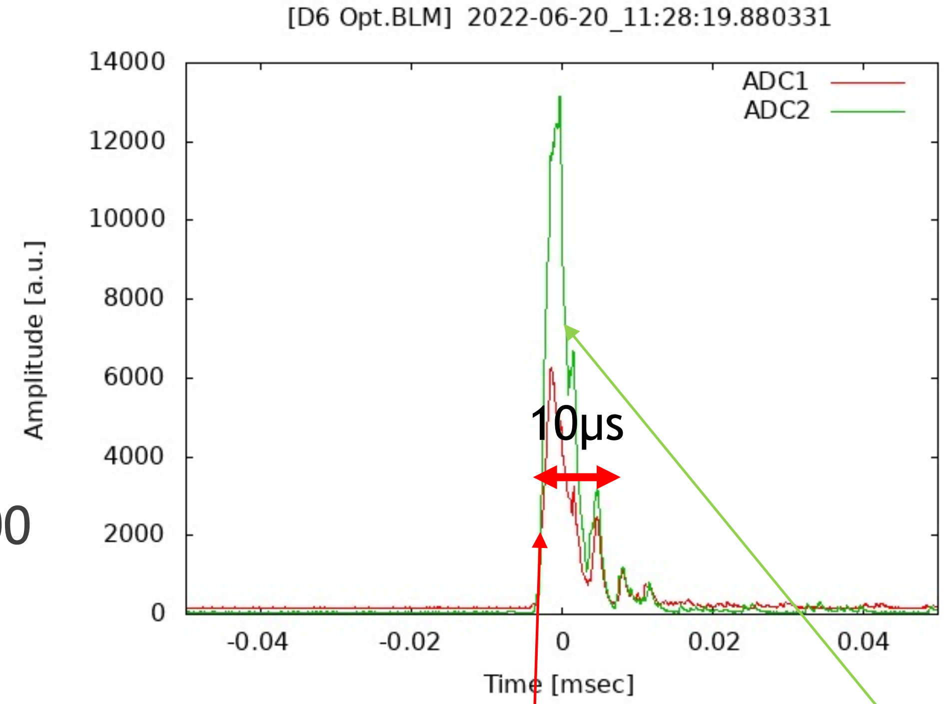
New sensor : Optical fiber

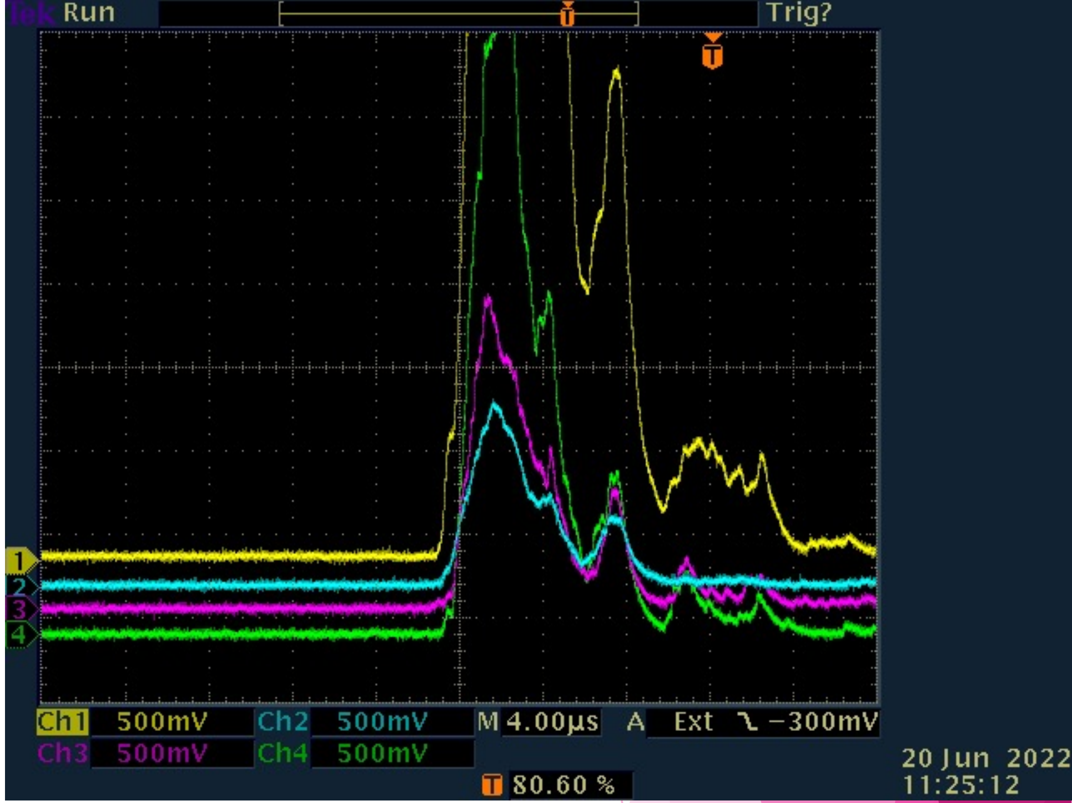
- The cause of the beam loss is unknown, but when the loss occurs, abort requested from the LM of downstream of collimator, Belle diamond, CLAWS, and also RF arc sensor.
- Since the loss monitor signal is sent to five LCRs around the ring, the cable length is not the shortest.
- In order to send abort signals at the minimum distance, a optical fiber was laid from the D6 power supply building to D6V2. After that, a single optical fiber is connected and extended upstream and downstream.
- The cable is input to PMT module and converted to electrical signals.
    - Capture/save waveform data
    - Trigger output by event detection (abort trigger)

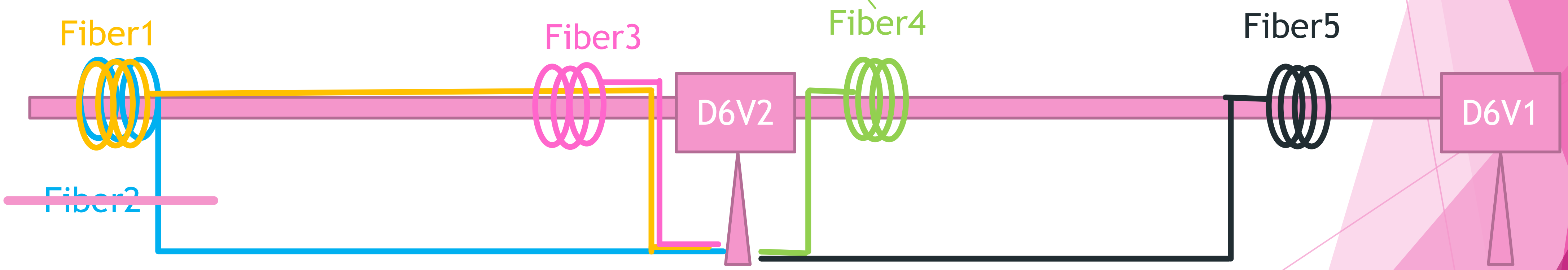


Beam Dump
BOR/BCM
Libera

- Threshold=1000
- ADC1 wid=3us
- ADC2 wid=5us

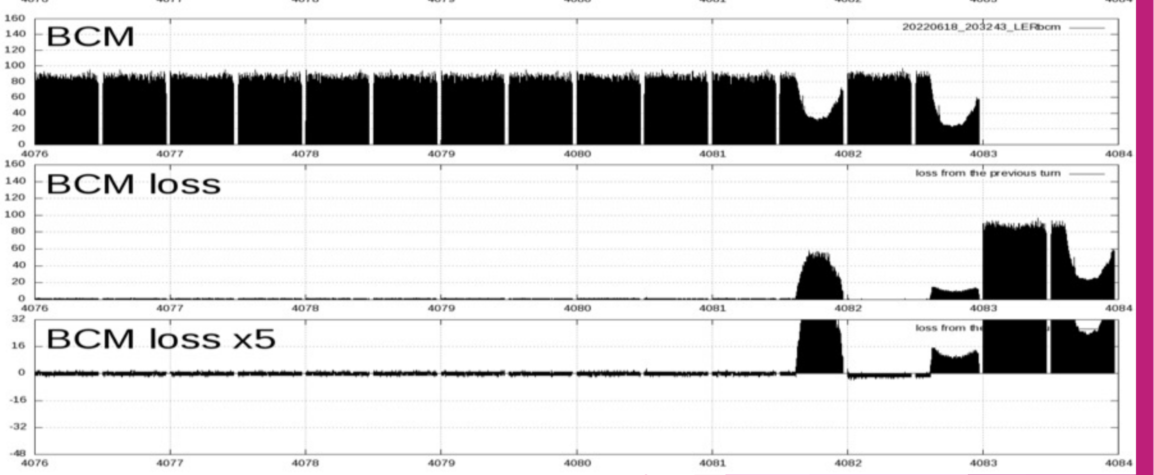






The time to issue the abort trigger has become several μs faster.

2. Sudden Beam Loss



- The biggest goal of SuperKEKB is to increase luminosity, but one of the obstacles is sudden beam loss.
- The cause of the sudden large beam loss is unclear.

→ Causes collimator (and other component)damage, QCS quench, Large B.G. to Belle-II.

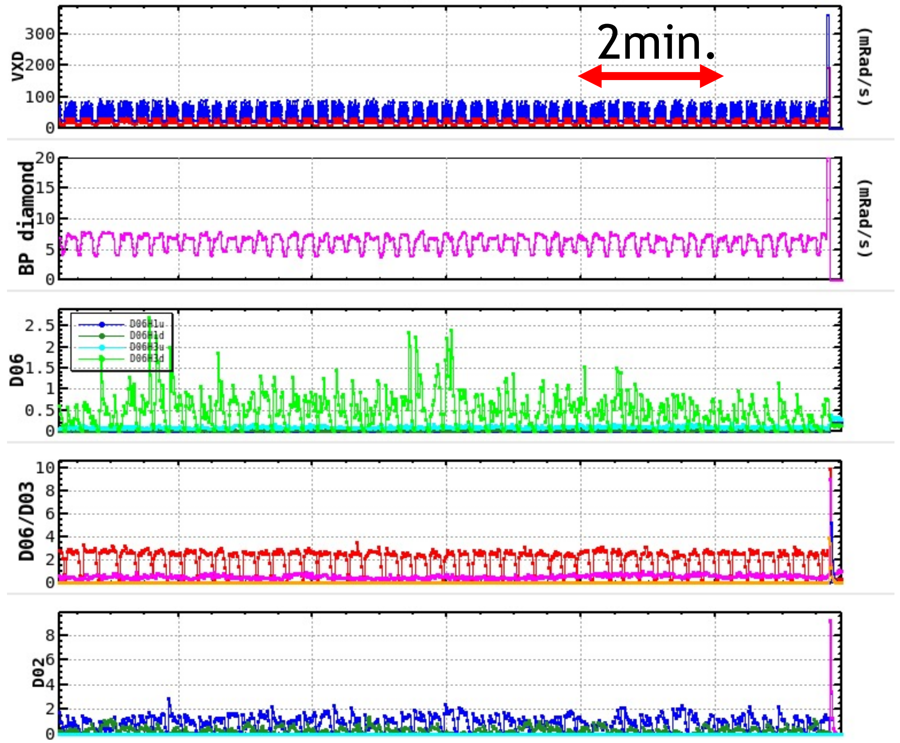
→ Cannot storage a large current since it causes beam abort.

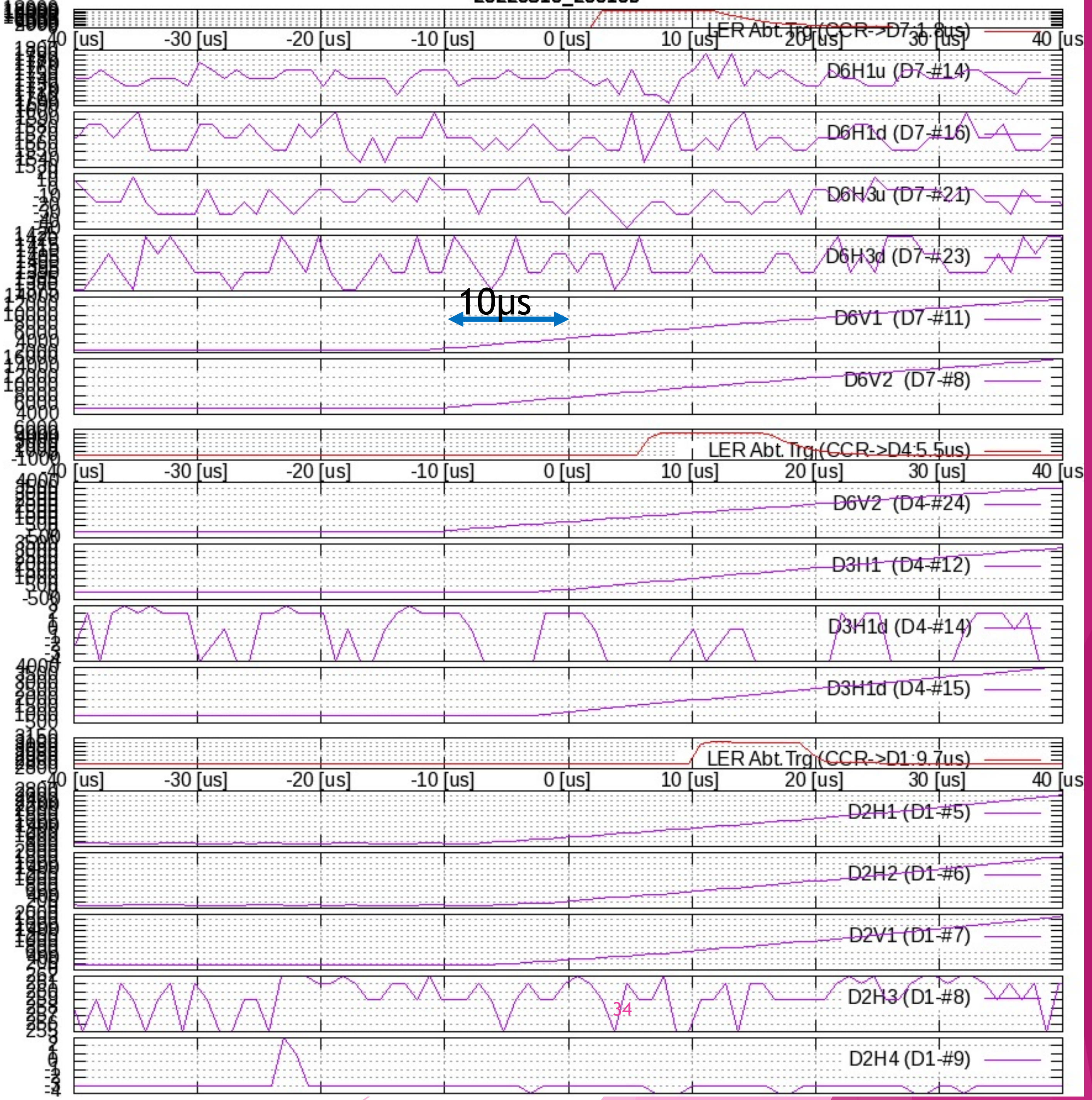
↓

- Start the task force to investigate and resolve the cause of the sudden beam loss.

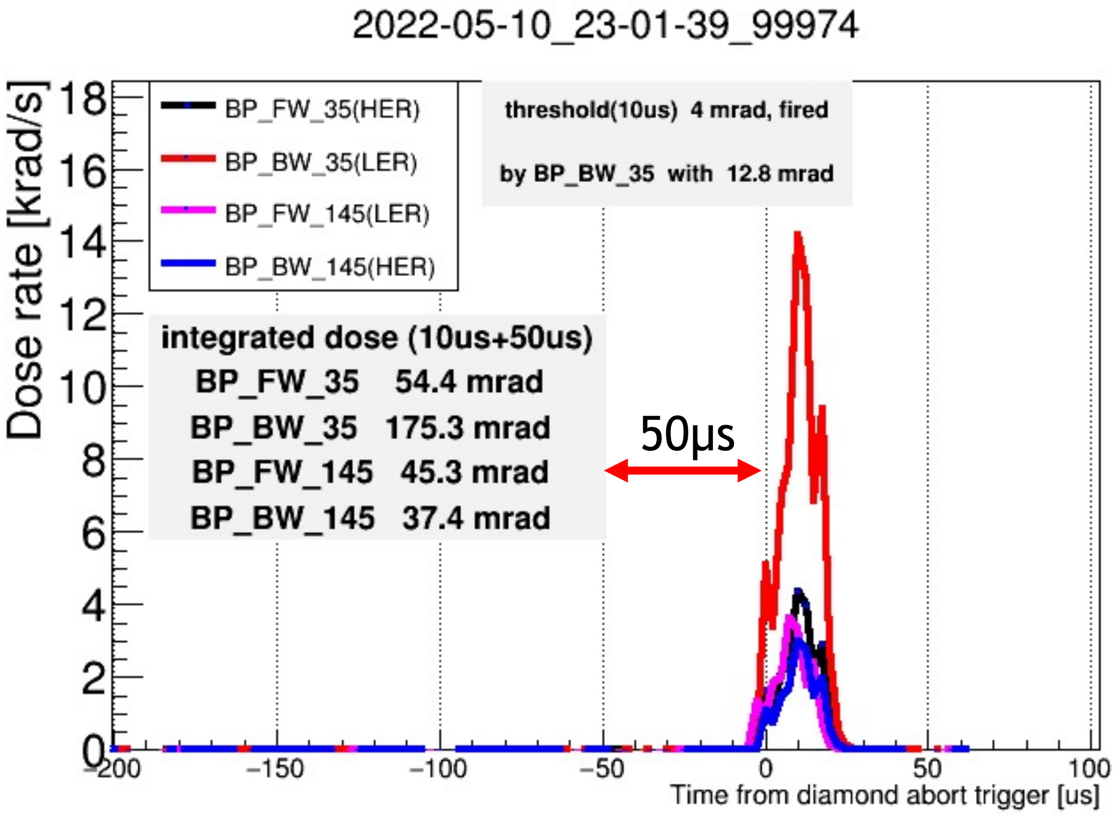
Observations : LM

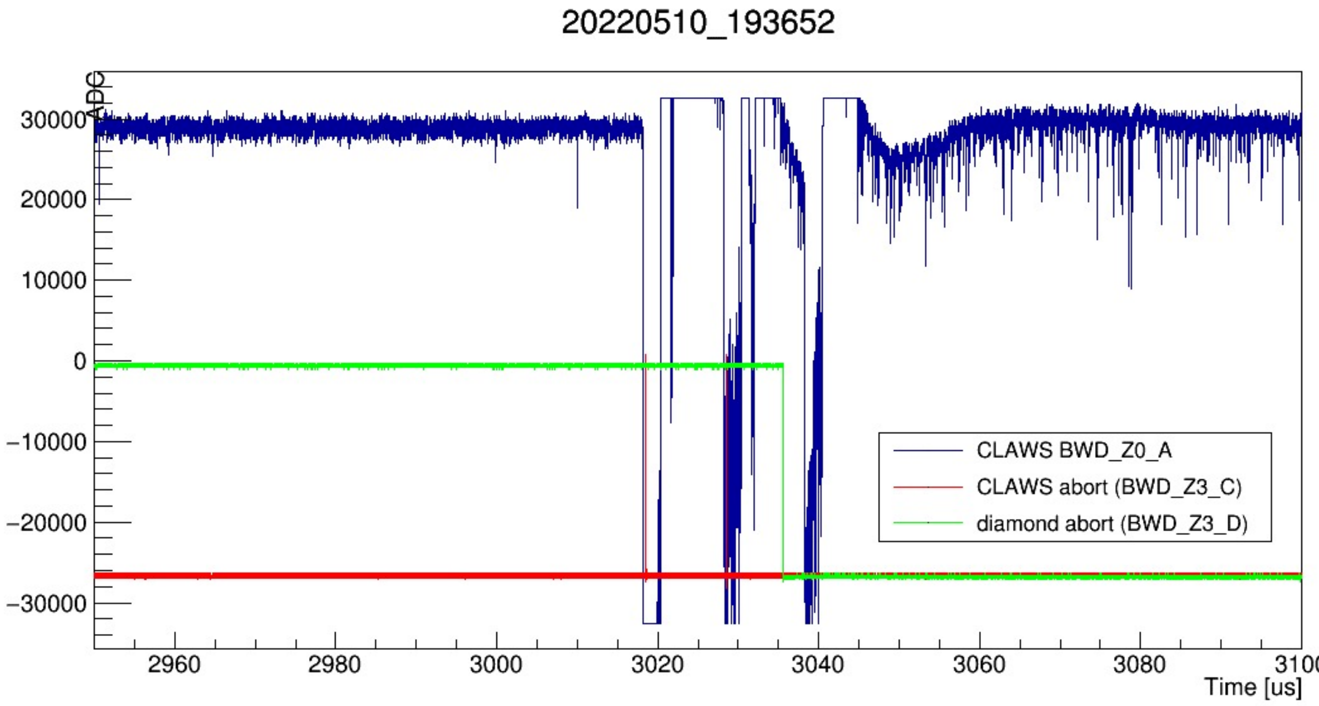
When we looked at the loss monitor when the abort occurred, which was thought to be caused by beam loss, beam loss looks started within one turn at the whole ring collimator part and Belle-II detector.





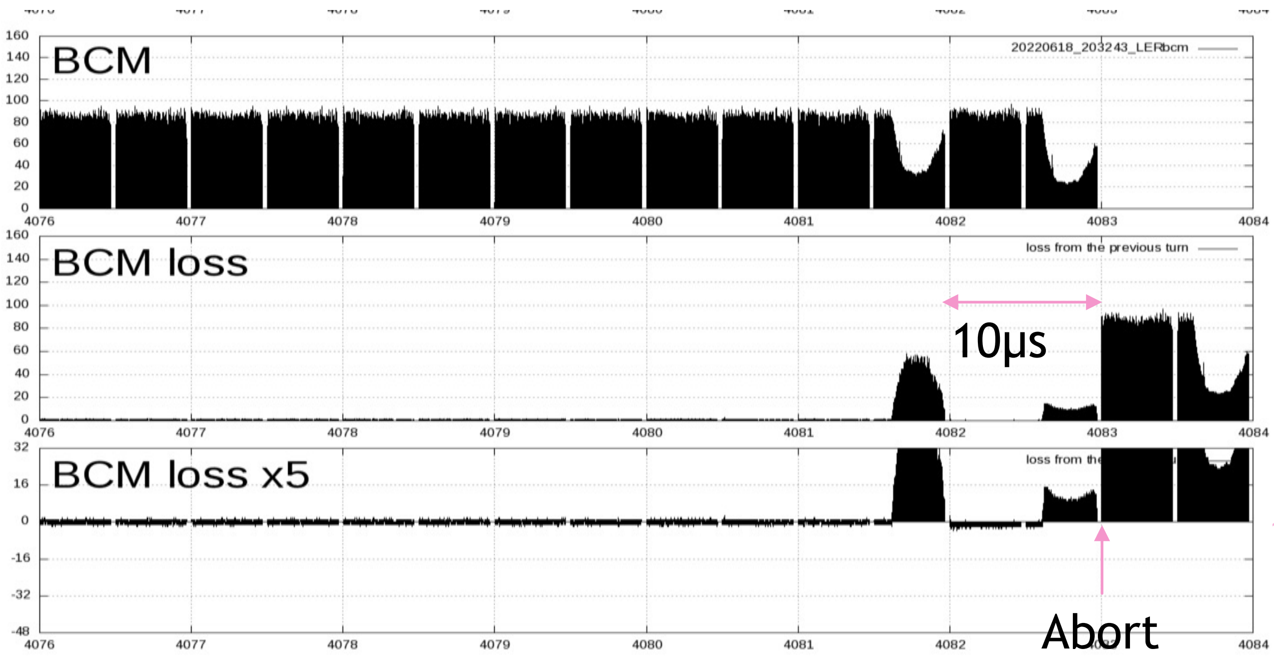
Observation : Belle dose

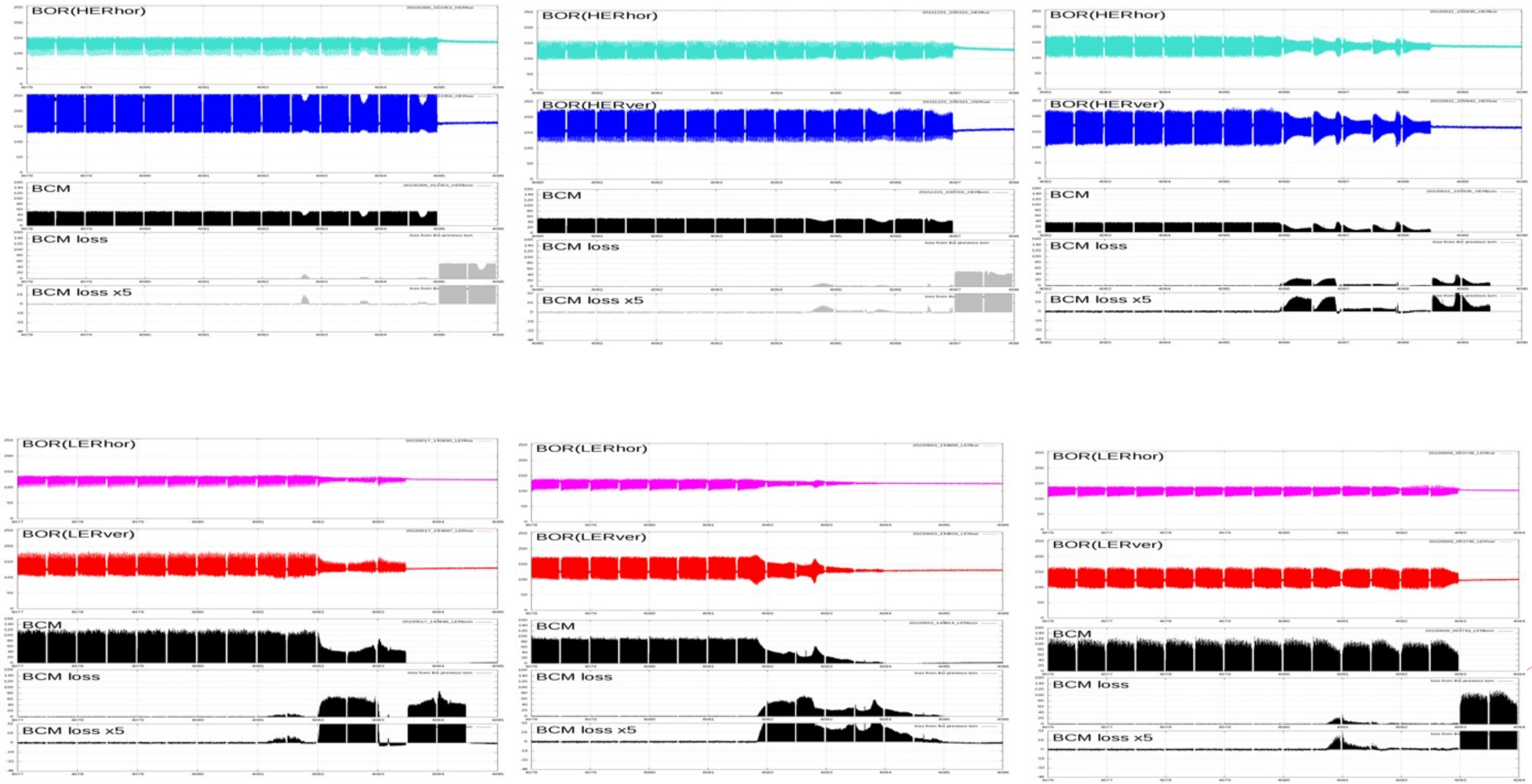




Observations : Bunch Current Monitor

- In order to investigate where in the train the beam loss started at the moment of beam loss, we recorded the bunch current 4096 turns before the abort trigger using feedback processors .
- Beam loss has been measured by bunch current monitor (BCM) to occur suddenly on a certain turn.

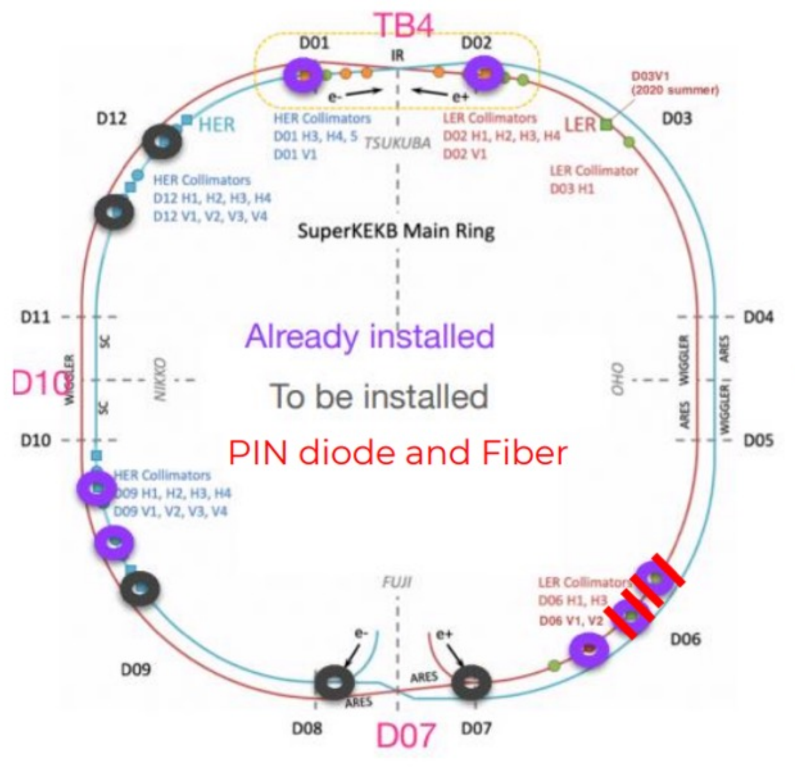


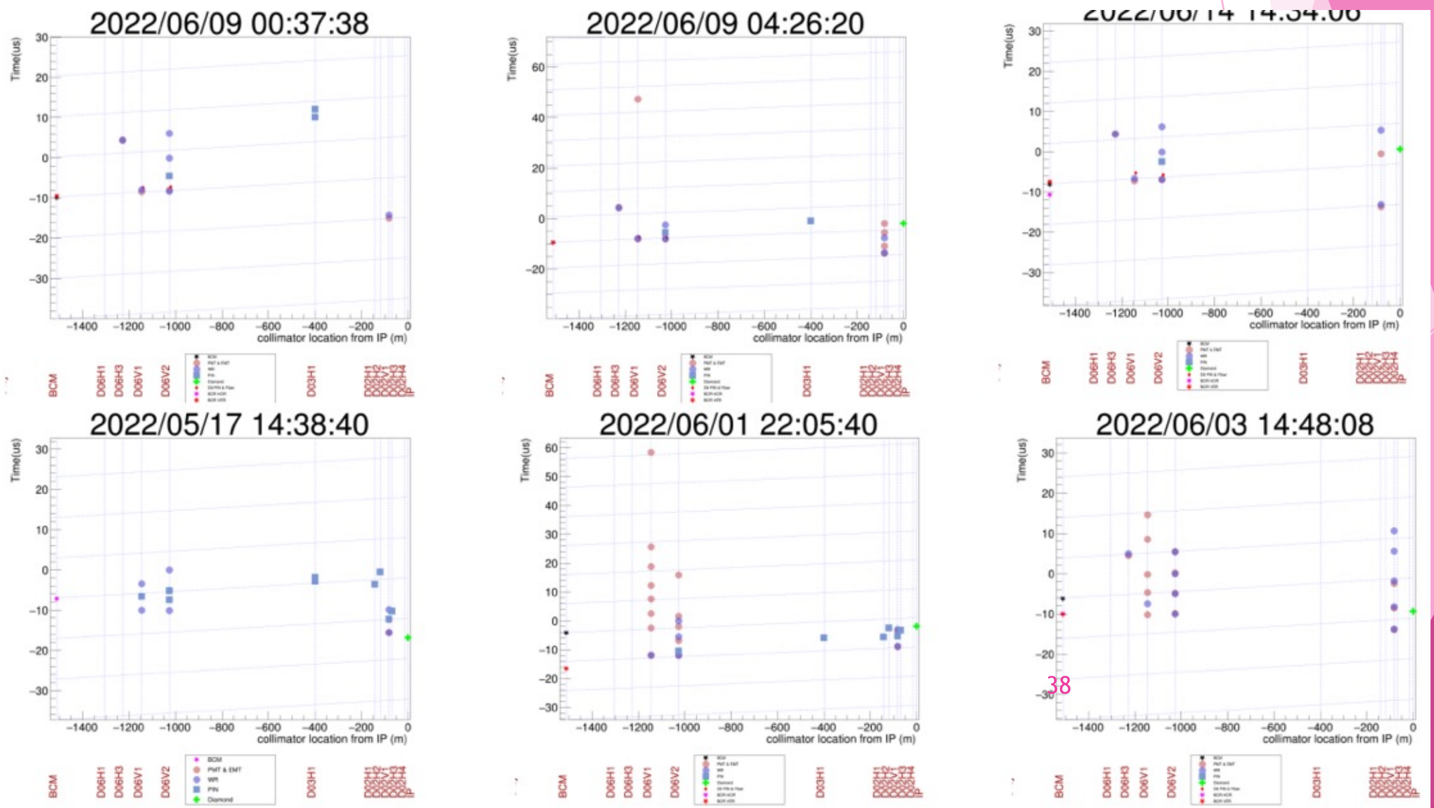


- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER.
- We don't know if it will happen even with a single beam operation, low current beam because we haven't operated for a long time.

Observations : Beam Loss Timing

- In order to find out where in the ring the beam loss first started, we installed a loss monitor specialized for timing measurement inside the ring.
- Beam loss occurs in collimator & IR, and where it occurs first depends on collimator tuning .





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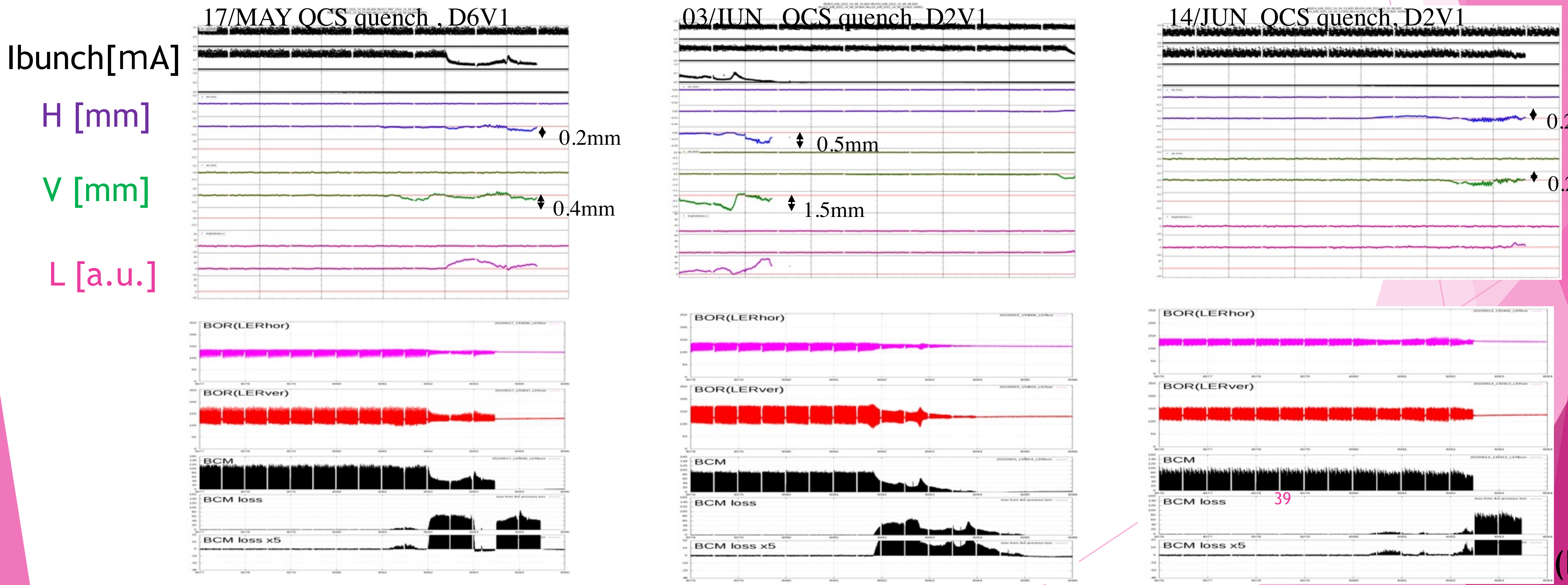
(Y.Liu)

Observations : Bunch Oscillation Recorder (BOR)

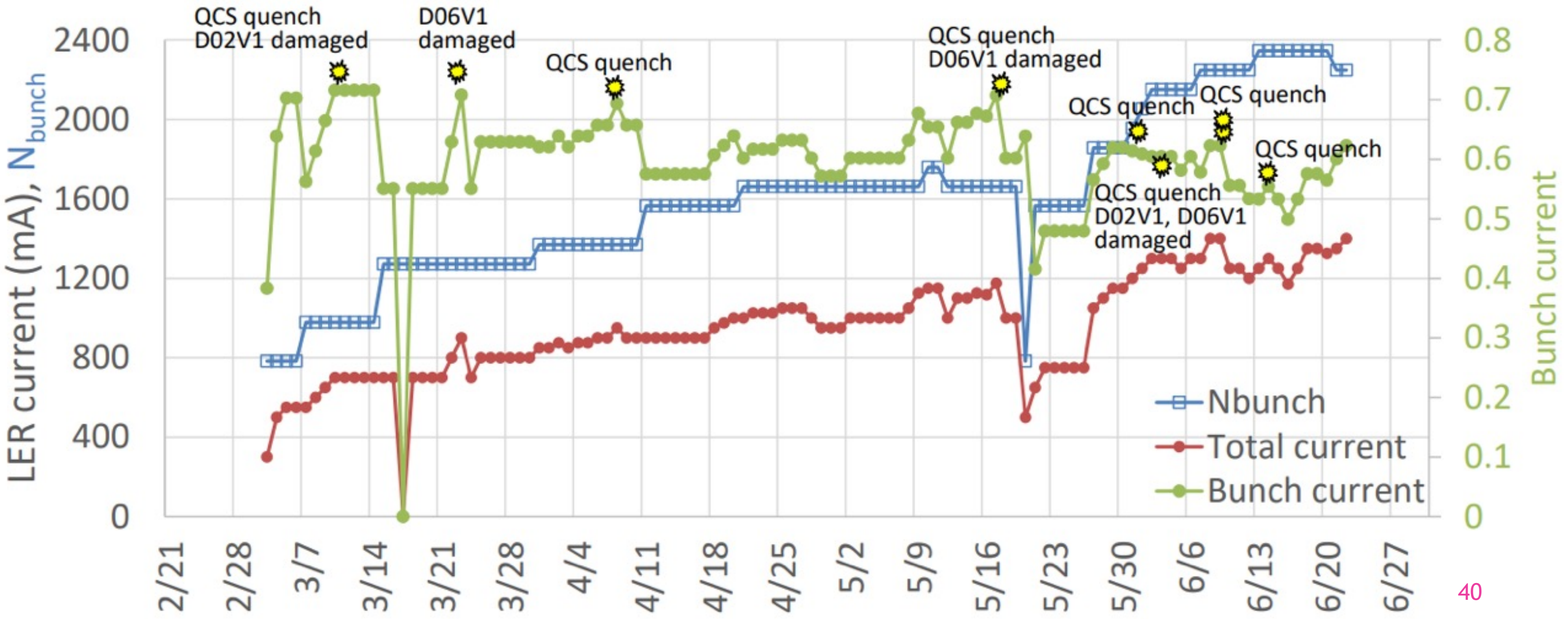
- The Bunch oscillation is measured 4096 turns before the abort trigger using feedback processors and the orbit is calculated from the data.
  - The orbit changed small ～1mm@FB position



(H.Fukuma)

Observations : Bunch Current of Operation

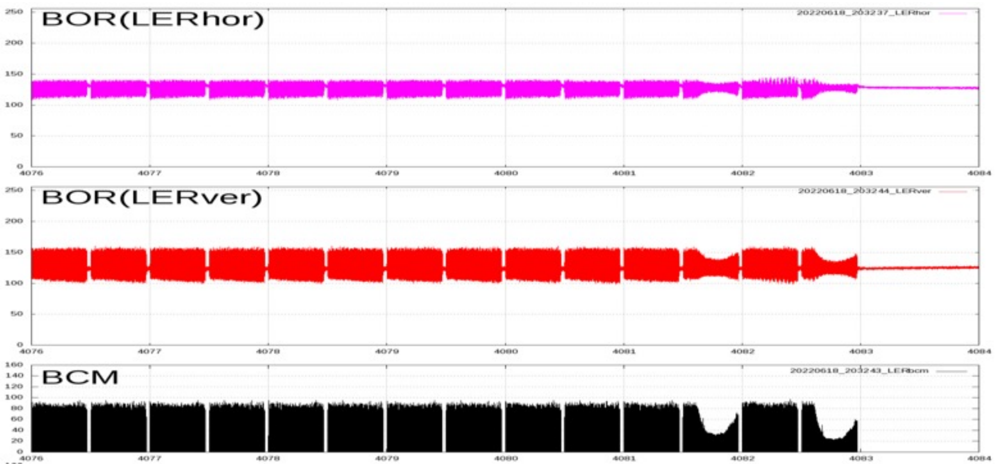
- It is likely to occur when a certain bunch current is exceeded.
- We don't know if it will happen even with a single beam operation, low current beam because we haven't operated for a long time.

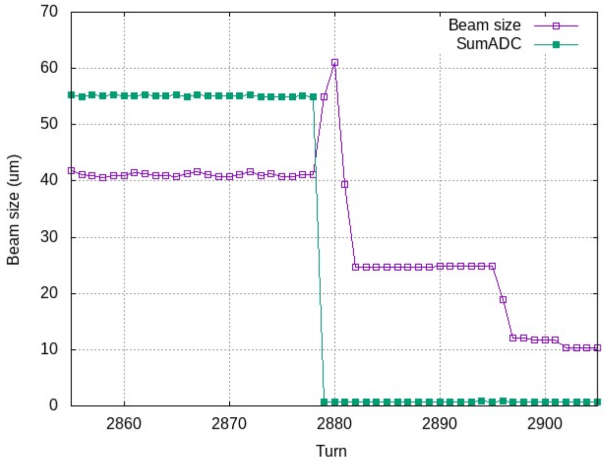


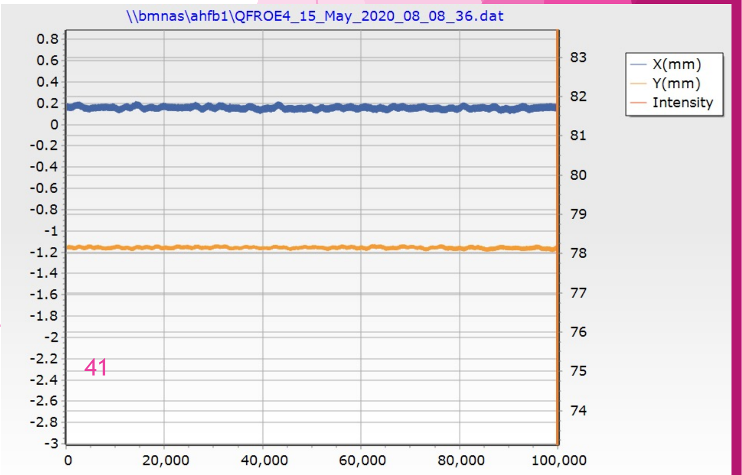
(K.Matsuoka)

Observations

- There are no signs before beam loss starting.
  - No small beam loss (beam loss monitor, BCM)
  - No oscillation (Bunch Oscillation Recorder (BOR))
  - No beam size change (X-ray monitor (XRM))
  - It is not clear if the orbit changed significantly.(Libera)

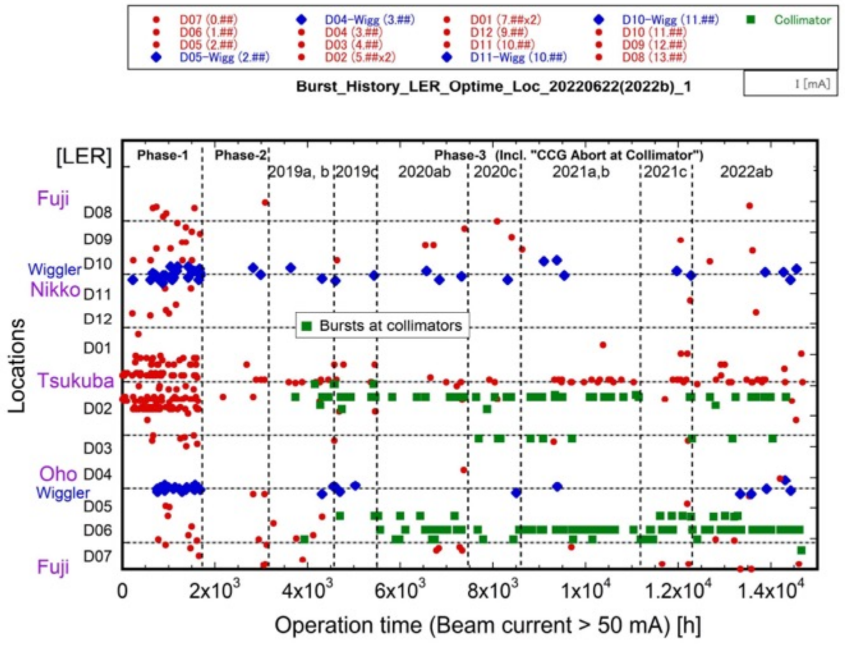


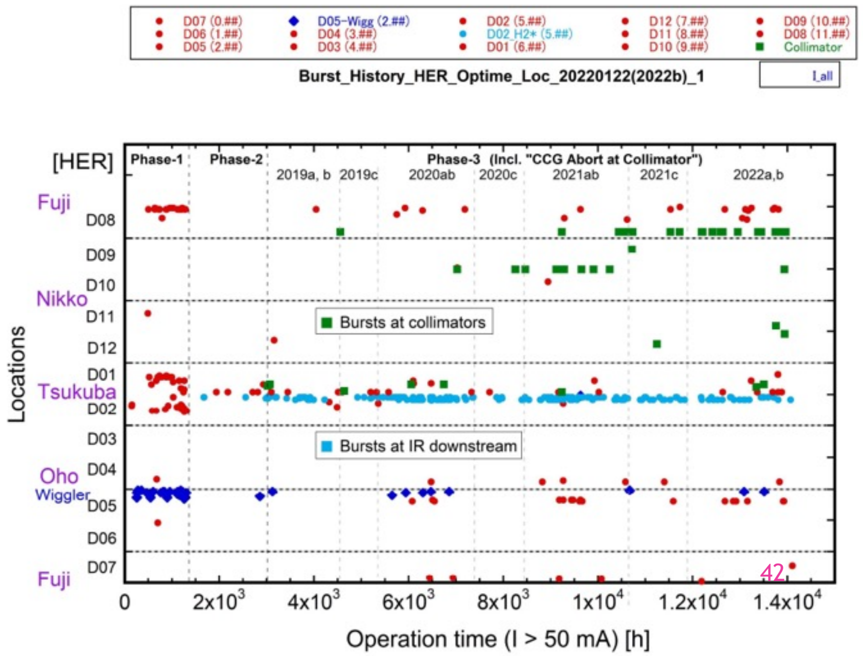




Observations : Vacuum

- Pressure bursts have been observed here and there, and it rarely occurs in the same place except in the collimator section. It may be the result, not the reason.

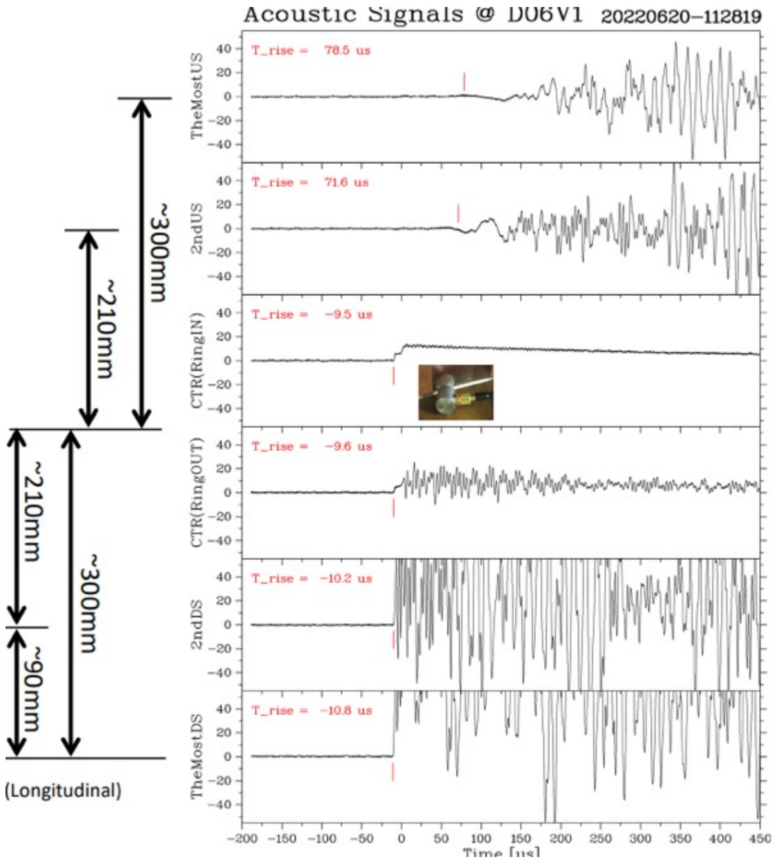


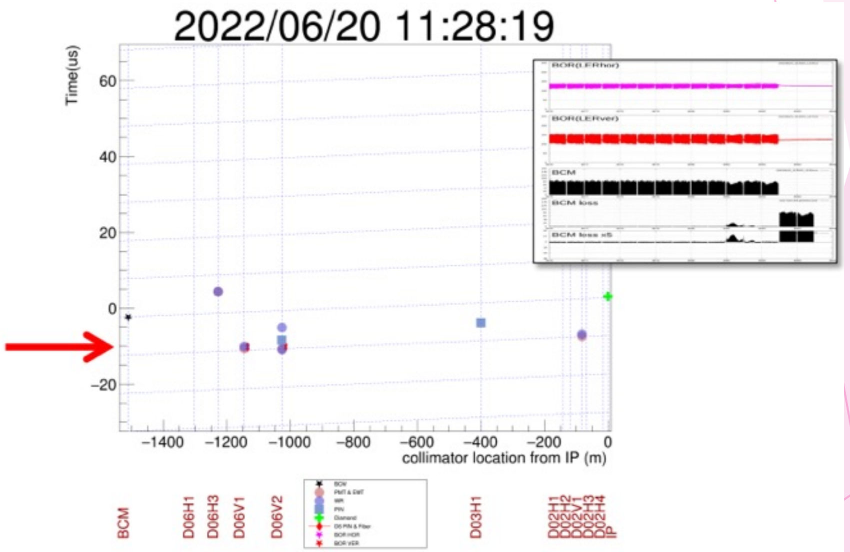


(Y.Suetsugu)

Observations : Acoustic waves

- Acoustic waves were detected at the same time with collimator beam loss.
  - We measure a few event before shutdown





Velocity of acoustic longitudinal (transversal) wave in copper: 4.65 (2.26) mm/us

This data suggests that the particle shower produced at the collimator head generated widespread acoustic wave in the downstream of the head, which propagated upstream.

(T.Abe)

Candidate of the beam loss reason

- There is no evidence that the place where the beam loss first occurred is the same (or close) as the place where the causative phenomenon occurred.
- Damage of vacuum component
  - Caused by damaged RF Finger @KEKB & PEP-II
    - phase changes (beam energy losses) had been observed ms ～ hundreds of μs before aborts.
    - abnormal temperature risings at bellows chambers had been observed and the catastrophic damages in the RF-finger had been confirmed.
    - It is imagined that the metal particles scattered by the arc discharge collided with the beam.
- Dust
  - Early stage @ SuperKEKB
    - Clean or hit the vacuum chamber to remove as much dust as possible.
- Fireball
  - Measured @ RF cavity

Future plans

- Visual inspection of the inside of the IR vacuum device (discharge marks…)
- Add new loss monitor for timing analysis
- Add BOR for another place on ring
- Setup acoustic sensors
- Check the temperature of vacuum component

- So far, there is no reliable way to investigate the cause of sudden beam loss

Loss Monitor : Summary

- In order to protect the hardware from dangerous beam loss, we are trying to speed up the abort trigger.
  - Increased the number of abort gap.
  - Introduce injection veto for LM.
  - Change the cable route and introduce new LM.
- One of the obstacles for luminosity increasing is sudden beam loss and the cause of the beam loss is still unclear.
  - We are investigating with Loss Monitor and other monitors, but no phenomena that clarify the cause have been found.
  - Start the international task force to investigate and resolve the cause of the sudden beam loss.